RTO-MP-16
AC/323(SCI)TP/8

RTO-MP-16

NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION
BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO MEETING PROCEEDINGS 16

Aircraft Weapon System Compatibility and Integration

(Compatibilité et intégration des systèmes d'armes aéroportés)

Papers presented at the Systems Concepts and Integration Panel (SCI) Symposium held in Chester, United Kingdom, 28-30 September 1998.

Published April 1999

Distribution and Availability on Back Cover

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The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

The total spectrum of R&T activities is covered by 7 Panels, dealing with:

- SAS Studies, Analysis and Simulation
- SCI Systems Concepts and Integration
- SET Sensors and Electronics Technology
- IST Information Systems Technology
- AVT Applied Vehicle Technology
- HFM Human Factors and Medicine
- NSPG NATO Simulation Policy Group (Modelling and Simulation)

These Panels are made up of national representatives as well as generally recognised 'world class' scientists. The Panels also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Printed on recycled paper

Published April 1999

ISBN 92-837-0007-4

Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7

Aircraft Weapon System Compatibility and Integration

(RTO MP-16)

Executive Summary

Weaponry is a central factor in any kind of military activity. The incorporation of weapon systems into aircraft and their integration and satisfactory operation is a topic of major importance to armed forces and manufacturers of weapons and aircraft alike. The scope of this symposium was to critically review the overall state-of-the-art in aircraft weapon system compatibility and integration and to illuminate possible paths for future development and provide beneficial ideas and experience. Sessions dealt with the following topics:

- Theoretical methods and modelling techniques
- Experimental and flight test techniques
- Integration processes and programmes
- Addressing future challenges

This symposium produced many excellent papers providing broad coverage of the weapons integration issues. There were many common threads with regard to the analysis, wind tunnel testing, and flight testing. Computational fluid dynamics (CFD) is proving to be a useful technique; wind tunnel testing is very important in the weapons integration process; but, flight testing has to be the final phase of the weapons integration process. This symposium produced a level of cohesiveness between the analysts and testers; however, full agreement as to the mix of analysis and testing did not evolve. In order to reduce the cost of weapon integration, certification, clearance, and flight testing, weapon integration analytical techniques, including CFD and wind tunnel testing, and flight testing need to become more of an integrated process. The knowledge gained and information shared at this symposium should assist the participants in developing a more integrated process in order to provide NATO nations with fully integrated weapon systems at an affordable price.

Compatibilité et intégration des systèmes d'armes aéroportés

(RTO MP-16)

Synthèse

Les systèmes d'armes sont l'un des éléments clés de toute activité militaire. L'incorporation des systèmes d'armes dans les avions de combat, leur intégration et leur mise en œuvre est un sujet qui revêt une grande importance pour les forces armées, les fabricants de systèmes d'armes et les avionneurs. Ce symposium a eu pour ambition de faire le point de l'état actuel des connaissances dans le domaine de la compatibilité et de l'intégration des systèmes d'armes aéroportés, de mettre en lumière d'éventuelles voies de développement futures et de proposer des idées et de l'expérience susceptibles de faire avancer les travaux dans ce domaine. Les différentes sessions ont traité des sujets suivants :

- méthodes théoriques et techniques de modélisation
- techniques expérimentales et techniques d'essais en vol
- programmes et procédures d'intégration
- relèvement des défis de l'avenir

Ce symposium a permis la présentation de bon nombre de communications de haut niveau, couvrant une large gamme de questions relatives à l'intégration des systèmes d'armes. Beaucoup de préoccupations communes ont été évoquées en ce qui concerne l'analyse, les essais en soufflerie et les essais en vol. L'aérodynamique numérique (CFD) se révèle comme une technique intéressante; les essais en soufflerie sont très importants pour l'intégration des systèmes d'armes, mais les essais en vol restent la phase critique de cette intégration. Ce symposium a vu un bon niveau de cohésion entre les analystes et les responsables d'essais, mais aucun accord global n'a été trouvé sur le partage judicieux à faire entre l'analyse et les essais.

La diminution du coûts de l'intégration des systèmes d'armes, de la certification, de l'homologation et des essais en vol, passe par le regroupement des techniques analytiques d'intégration des systèmes d'armes, y compris le CFD et les essais en soufflerie, et les essais en vol en un véritable processus intégré. Les connaissances acquises et les informations échangées lors de ce symposium devraient aider aux participants de développer un processus plus intégré, afin de permettre de fournir aux pays membres de l'OTAN des systèmes d'armes totalement intégrés pour un coût abordable.

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†Paper not available at time of printing.

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Acknowledgements

The Systems Concepts and Integration Panel wishes to express its thanks to the National Authorities of the United Kingdom for the invitation to hold this symposium in their country.

TECHNICAL EVALUATION REPORT

by

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• SUMMARY

This report presents a review of the technical material presented at a symposium sponsored by the Systems Concepts and Integration (SCI) panel of the NATO Research and Technology Organization. The intent of this report is to provide a brief evaluation of the symposium and the material presented, plus implications for future symposia on aircraft weapon systems compatibility and integration. But, first it is relevant to reflect on the genesis of the SCI panel.

• BACKGROUND

NATO's Research & Technology Organization (RTO) is an outgrowth of the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). Both AGARD and DRG share common roots in that they were both established at the initiative of Dr. Theodore von Karman, a leading aerospace scientist, who early on recognized the importance of scientific support for the Allied Armed Forces. RTO is capitalizing on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future. The Systems Concepts and Integration (SCI) Panel is one of six panels in RTO, formed in the late 1990's, that encompass the full spectrum of research and technology activities. The SCI Panel is concerned with the advanced systems concepts, integration, engineering techniques, and technologies across the spectrum of platforms and operating environments to assure cost-effective mission area capabilities. Integrated defense systems, including aerospace, land, sea, and space systems (manned and unmanned) and associated weapon and countermeasure integration are covered. The scope of the SCI Panel activities covers a multidisciplinary range of theoretical concepts, design, development test and evaluation methods applied to integrated defense systems. Areas of interest include: Integrated Mission Systems, System Architecture/Mechanization, Vehicle Integration, Mission Management, and System Engineering Technologies and Testing.

From a historical perspective, this SCI Panel symposium on Aircraft Weapon System Compatibility and Integration seems to be timely to reflect on the current status. Many integration issues arise when integrating older/mature weapons on new aircraft or modern smart weapons on existing aircraft that may have been in tactical operations for 10-20 years.

• INTRODUCTION

This third Symposium of the Systems Concepts and Integration Panel was

held in Chester, United Kingdom 28-30 September 1998. The symposium was titled **AIRCRAFT WEAPON SYSTEM COMPATIBILITY AND INTEGRATION.** The symposium was attended by 127 engineers and scientists from numerous NATO and non-NATO nations.

Since weaponry is a central factor in any kind of military activity, the incorporation of weapon systems into aircraft and their integration and satisfactory operation is therefore a topic of major importance to armed forces and manufacturers of weapons and aircraft. Most NATO nations devote significant resources to aircraft/weapon system integration work and compatibility challenges.

Current world economics and threat situations dictate that the life span of existing aircraft must be stretched, making integration of new weapon/weapon systems into existing airframes necessary. Likewise, these same constraints dictate the corollary, i. e. new aircraft must be compatible with existing weapons.

This symposium critically reviewed the overall state-of-the-art in aircraft weapon system compatibility and integration for the benefit of researchers, RDT&E managers, engineers, and operational staff employed by both customer and supplier organizations within NATO and, hence, intended to illuminate possible paths for future development and provide beneficial ideas and experience. Surprisingly, this is the first conference specifically dedicated to weapons that has been sponsored by AGARD or DRG (now RTO). The symposium was divided into the following four sessions in which 26 technical papers were presented:

SESSION I. THEORETICAL METHODS & MODELLING TECHNIQUES

SESSION II. EXPERIMENTAL AND FLIGHT TEST TECHNIQUES

SESSION III. INTEGRATION PROCESSES AND PROGRAMMES

SESSION IV. ADDRESSING FUTURE CHALLENGES

Additionally, two keynote address were given plus a round-table was held at the end of the symposium.

- **THE TECHNICAL PROGRAM**

- **KEYNOTE ADDRESSES**

The technical program was opened with two excellent keynote addresses. The first keynote address was presented by Dr. C. Pell, Directorate of Science (Air), Ministry of Defence, United Kingdom. Dr. Pell discussed weapons' military/technical drivers and how the military drivers (mission effectiveness, survivability, lethality, and affordability) translate into technical drivers for aircraft/weapon integration. Technical considerations for aircraft/weapon integration are minimizing aerodynamic drag and signatures while ensuring safe and effective release of the weapon. Dr. Pell connected the technical drivers to the mission phases of carriage, release, and post-release.

Dr. Pell presented a brief but informative synopsis of the counteracting forces/trade-offs when carrying weapons on an aircraft. Considerations of weight, drag, signature, operating range, internal/external carriage, flutter, flight envelope, flight clearance, and the

myriad of weapons from dumb bombs to sophisticated smart bombs and missiles are challenges that the designer and integrator have to properly balance to have an effective integrated weapon system that will satisfactorily perform the military mission. More complex weapon shapes including complex wing and fin arrangements and stealthy shapes, many being unstable, plus the issues that arise from internal carriage in a bomb bay further make the task of the weapons integrator arduous. Dr. Pell emphasized a point that, in spite of the strides being made in the use of wind tunnels and advances in computational fluid dynamics (CFD), flight testing will remain the final arbiter of success in aircraft/weapon compatibility and integration. His "way forward" emphasized standardization across all NATO nations and using a systems approach as the best process to optimize the balance between mission effectiveness and affordability.

. The second keynote address was given by Rear Admiral J. V. (Jocko) Chenevey, U. S. Navy, Assistant Commander for Logistics and Industrial Operations, Naval Air Systems Command. Rear Admiral Chenevey addressed weapon systems from sustainment in the context of being able to sustain the strength of the aviation arms of our respective armed forces. He expressed concern with the ability to replace the aging aircraft inventory as it attrites. He projected that 85% of the U. S. Navy inventory that we would take into a conflict in 2010 are already in the inventory. The Admiral spoke of recapitalization and modernization of the armed forces. Recapitalization requires a significant budget while modernization, or updating the existing inventory to meet current and expected future threats, is generally more affordable and provides new capability to the warfighter quicker. Decisions have to be made to obtain the most from the limited DOD dollars. Admiral Chenevey's closing statement is "we need to venture boldly but on a calculated path that gets us to where we are increasingly contributors not just to greater combat capability but to the overall sustainment and vitality of our combat aviation assets."

- **THEORETICAL METHODS & MODELLING TECHNIQUES**

All six papers scheduled for Session I, Theoretical Methods & Modelling Techniques, were presented. These papers provided good coverage of modeling techniques pertaining to stores carriage, separation, trajectories, loads and flutter.

Paper 1 presented an analysis of Applied Computational Fluid Dynamics (ACFD) as a tool for use by the aircraft store certification organizations. The paper discussed the results of a specific CFD code that appeared to be superior to others in providing answers at transonic speeds in a reasonable amount of computational time. CFD analysis was conducted on a U. S. Navy F-18 with a JDAM on the outboard wing pylon and a 330 gallon fuel tank on the inboard pylon. Wind tunnel data and flight test data had shown a decrease in moments from M=0.8 to M=0.9. For CFD to be useful, it had to be capable of predicting this type of behavior. Conclusions drawn from this analysis clearly show that at the present time CFD can not be expected to accurately provide a good estimate of store carriage loads and trajectories in a reasonable amount of computational time. Solution time in the order of

months on a workstation may be needed to achieve a convergent Euler solution.

The British Aerospace 6 degree of freedom (dof) simulation toolset, called STARS, is the subject of **paper 2.** Using a range of simulation techniques, the models for analyzing store separation can be created and executed using a graphical user interface and trajectories visualized in a 3D animation. The core of the simulation is a 6 dof executable library objects using 4th order Runge-Kutta integration of body motion, including any change of mass effects. The models allow many tolerance conditions that can be studied safely and cost effectively. Use of this tool has allowed more focussed flight trials with possible reduction of flight trials required.

Paper 3 discussed a validation of CFD approach for store separation trajectory predictions for missiles. The paper presented comparisons of CFD results with flight test data and wind tunnel data. The authors also define which analysis techniques are most useful, e.g., the grid approach has some advantages but also has limited use. Some good comparison is provided for releases from a Mirage 2000 which show good comparison of lift and pitching moment. Issues with using CFD is the cost.

Aeroelastic methods for predicting wing/store flutter and dynamic loads of fighter type aircraft is the topic for **paper 4.** Fighter type aircraft are usually required to carry a large variety of stores thereby causing much concern about wing flutter. The National Aerospace Laboratory of the Netherlands uses unsteady aerodynamic modeling to simulate the classical and non-linear flutter stability. The paper describes various flutter calculations for the F-5 aircraft. Various modes of flutter are shown for the F-5 aircraft at M=0.9. The author foresees more CFD analysis in the future for flutter computations.

Paper 5 presents the CFD analysis of the integration of the Joint Direct Attack Munitions (JDAM) store on the U. S. Navy's F/A-18C. The results showed reasonable correlation with available wind tunnel test data across a wide angle-of-attack range at both transonic and supersonic flow conditions. The CFD results were analyzed to explore the aerodynamic influences on an adjacent 330 gallon fuel tank to develop a flight clearance for carriage of the JDAM store. The author points out that the CFD and finite element structural analysis was available eight days after receipt of the JDAM geometry. The entire aerodynamic and structural analyses were completed in three weeks and resulted in a successful flight test program. Conversely, conventional wind tunnel tests to achieve this same data was projected to take up to nine months.

A method of predicting weapon ballistics prior to flight trials using existing six degree of freedom modeling at British Aerospace is the topic of **paper 6**. The paper shows the benefits accrued by using the safe separation models to provide trajectory data ahead of any flight trials and how it can improve the accuracy of ballistic data and the ground impact pattern supplied prior to any flight trials. The author contends that this approach using the safe separation model to provide trajectory data should result in lower initial ballistic errors and, therefore, fewer flight trials. No data is provided to substantiate this claim.

• EXPERIMENTAL AND FLIGHT TEST TECHNIQUES

In this session on experimental and flight test techniques, five papers were presented. Several interesting approaches to gathering test data on weapon carriage, separation, and ballistics were presented along with some interesting flight test programs.

Paper 7 presents the test results from surface pressure measurements on a 6% scale model of the F-18 in a Trisonic Blowdown Wind Tunnel using pressure sensitive paint (PSP) technique. The recently developed PSP technique is attractive for surface pressure measurements without the need for elaborate sensor installations. Test results showed that temperature has a significant effect on the luminescent intensity PSP measurement. Useful data was still obtained after the tunnel startup transient. PSP techniques and the images generated serve as a very useful and indicative flow visualization tool. Shock waves and their locations can be readily recognized on the model surface. Good comparison with conventional pressure transducer data was obtained for M=0.8 at angle of attack of 4.5 deg but not so good at M=0.6. Test showed reasonable agreement with predictions from CFD codes.

Methods and applications of photogrammetrics for aviation test and evaluation is the topic of **paper 8**. Photogrammetry is the use of multiple sequential recorded film and video images and is used for evaluation of stores separation, carrier suitability, ballistic trajectory tracking, overhead impact scoring, and mishap reconstruction. This paper presents the broad use of photogrammetry and details how the images are processed from single or multiple cameras. The authors further described how their team met the challenge of processing high volumes of photogrammetric data and delivering solutions within 72 hours of each flight for the F/A-18E/F.

Paper 9 presents Alenia's approach to store separation on combat aircraft including jettison safety. The activities are carried out in three phases: pre-flight analysis, flight trials, and post-flight analysis. Pre-flight analysis includes aero modeling including the use of computational fluid analysis. Bomb separation trajectories are computed using the mathematical model, Store Separation Trajectory Programme. Flight trials use onboard cameras as the primary source of data for store separation trajectories. Post flight analysis uses flight data to match and validate the mathematical model used for the pre-flight analysis. New tools developed by Alenia have shown significant improvements to the store separation analysis process. Test data presented shows reasonable correlation between predicted and flight test results.

Paper 10 presented future developments in airborne instrumentation and motion analysis systems for store separation. The authors make a plea and convincing argument for moving away from the conventional cine-cameras to high speed digital video cameras capable of frame rates up to 2,000 frames/second. This is the way of future store separation filming being considered by many countries since high speed digital video is becoming a very useful tool with long term cost savings and environmental benefits. Qualities of a digital high speed video system are presented along with the requirements.

The paper advocates converging to a universal standard platform for the deployment of imaging. The author identifies three main aspects of a motion analysis system for store separation. They are: The creation of the three dimensional geometry which provides the framework for the measurement space, the image recognition technique which is used to track the store image, and the estimate of the three dimensional position and attitude from the two dimensional tracking. The paper goes on to define how British Aerospace has developed a software system which will ultimately provide fully automatic six degree of freedom analysis.

The integration of the GBU-24 Laser Guided Bomb on the U. S. Navy's F-14 TOMCAT is the topic of **paper 11**. Because of the GBU-24 large size and large deploying wing, a more integrated approach to clearing the bomb needed to be employed. The process consisted of computational analyses, wind tunnel testing, ground testing, flight testing and photogrammetic analyses. The integration tests discussed in this paper showed how full use of analytical and wind tunnel techniques were essential in the clearance of a large (2,000 lbs.) weapon with canards. The GBU-24 was ultimately cleared for carriage and release on F-14 fuselage stations.

Paper 12 presents the ground and flight testing to structurally qualify the Hellfire Missile System and the nose mounted Forward Looking Infrared (FLIR) with laser designator system installation in the H-60 helicopter for the U. S. Navy. A six degree of freedom simulation was used to develop the minimum number of test points to clear the desired envelope while managing risk. The paper provided a very detailed description of the testing performed to qualify the installation but provided very little data. Many acronymns are used throughout the text.

The U. S. Navy's integrated approach to store separation analysis is presented in **paper 13**. This integrated approach employs a combination of wind tunnel testing, flight testing, and computational aerodynamic analysis. This integrated approach, as depicted in the triangle diagram, shows how the different disciplines complement each other and provide feedback to continually update the models for the weapons integration process. This integrated approach stood out from all the papers as a most effective technical approach of using all the tools for stores separation integration and analysis. The author presented the F/A-18E Joint Stand-off Weapon (JSOW) as an example of using this integrated approach. Several comparison charts are presented showing a comparison of the clean (no pylon) F/A-18C and the F/A-18E. Flowfield analysis was conducted to identify potential store separation issues.

Paper 14 describes the analysis done to eliminate or reduce a major weapon separation problem discovered in the transonic wind tunnel on the U. S. Navy's F/A-18E/F airplane. The separation problem discovered prohibited the F/A-18E/F from meeting the release and jettison specification requirement. Many concepts were considered and screened by a subsonic panel method and CFD to select the concept for wind tunnel testing. The author provides many charts of wind tunnel test data resulting in a configuration called pylon doors that produced the best overall

improvements in trajectory and miss distances but was unpopular with pilots and would have caused significant program delays if implemented. A pylon toe system was the next best fix that both the U. S. Navy and the contractor could live with. The paper is a good description of how wind tunnel testing was used to resolve a known weapon separation problem.

Paper 15 presents the Australian perspective of aircraft/stores compatibility. There was no paper provided and only viewgraphs were presented at the symposium. The thrust of the presentation was to show the technical approach and organizational structure of how the Australians conduct the compatibility testing and clearance process. Their processes, their organizational structure, and philosophy is similar to that of the U. S. The Australians are now the only operators of the F-111 airplanes. They, like most other countries, have to work the integration issues of old and new aircraft and old and new weapons.

The programmatic considerations of integrating a weapon system into an existing aircraft is the topic of **paper 16**. The paper addresses the factors one works with to procure a retrofit kit to meet the evolving U. S. Navy's P-3C ORION airplane. The paper addresses policy and politics, technical considerations including analog vs. digital, man machine interface concerns, flight testing, use of non-military standards, COTS (Commercial Off The Shelf) or NDI (Non Developmental Item). The paper presents an interesting discussion of all the issues facing a program manager in a dynamic world where industry is "hungry" and budgets are being reduced. Simulation Based Acquisition (SBA), a new approach to procurement currently being used by the U. S. Department of Defense, is discussed.

Paper 17 presents the integration of a mast mounted sight on the Tiger helicopter. The paper and presentation discusses, in great detail, the mechanical integration and decoupling of the sight from the helicopter rotor system. Ground and flight trials are presented. Integration risks are discussed. Finite element analysis was performed to model the mechanical integration.

Paper 18 gives an overview of the rotary wing stores integration process improvements for the U. S. Army. The processes were improved, made more efficient, and resulted in reduced costs of clearing a firing or jettison envelope for a new helicopter/weapon combination. The paper describes the improved processes, new tools developed, and the efficiencies achieved. Further improvements in simulation, computing power, and the use of digital cameras need further concentrated efforts.

An informative overview and synopsis of the AGARD lecture series on helicopter/weapon system integration is provided in **paper 19**. The lecture series reviews current operational helicopters in the NATO countries and focuses on lessons learned with recent helicopter weapon system integration efforts. Selected aspects of the case histories presented in the lecture series are discussed with the intent to cover the broad spectrum of specific solutions for modern helicopter/weapon systems and to draw some general conclusions. The paper stresses weapons integration considerations be incorporated in the

advanced design and test procedures rather than after the vehicle is fully developed.

Paper 20 presents the U. S. Navy's applications of modern multi-disciplinary approaches to integration of weapons on aircraft. In this paper, multi-disciplinary implies the perspective of systems engineering. The paper presents the evolution of using traditional methods of weapons integration to the modern approaches using MIL-A-8591 procedure B which takes aircraft interference effects and the development of modern aerodynamic load procedures. The central theme is the close coordination and collaboration between flight test and analysis efforts that led to successful application of the new analysis procedures. Several examples of the AIM-9 missile integration are presented that substantiate this multi-disciplinary/systems engineering approach.

Paper 21 describes how to deal with the increasing complexity of weapon integration to aircraft from a French perspective. The paper discusses the factors that increase the complexity including technical and budgetary constraints, interfaces and interactions with the aircraft are more complex, etc. An interesting chart showed the increasing integration complexities. Approaches to deal with the complexities involve integrated teams of the manufacturer and integrator plus involvement of the customer to identify problems early into the integration. The author describes several aspects of simulation including: operationally oriented to identify the environment, interaction of the aircraft and weapon, physical oriented simulation, etc. To increase range and payload while maintaining or improving mission survivability, weapons must be carried in low drag/low observable configurations.

Paper 22 presents wind tunnel test results that defined weapons bay baseline acoustic environment and to evaluate the effectiveness of active acoustic suppression techniques. Active suppression techniques investigated were leading edge oscillating flaps, leading edge pulsed fluidic actuation, and a high frequency tone generator. Even though up to 30 db of suppression was achieved for certain test conditions, it is obvious that much "fine tuning" of the full scale model will be needed to provide good acoustic suppression.

The intent of **paper 23** is to demonstrate the adverse effects caused by structural deformation of carriage devices and launch equipment, induced by lateral forces and moments, that is not accounted for in the prediction of weapon separation behavior for fighter aircraft carrying external stores. Simplified tests with a small intentional misalignment of less than 1 deg in roll and yaw show the effects of structural deformation. The author produces a convincing argument that structural deformation needs to be accounted for and discusses several experimental approaches and concepts that provide reasonable methods for its quantification.

Paper 24 presents a U. S. Air Force initiative for national/international cooperation to address weapon integration issues. The efforts are focused in three areas: integrated design/analysis software and data management, active control of weapons bay environments, and low drag, survivable external carriage options. The paper presents initiatives

over recent years to identify weapon integration problems. Example programs discussed include the F-4 Conformal Carriage program, weapon bay acoustics and acoustics suppression, wind tunnel, CFD, and neural network to predict weapon separation. The most recent initiative is called AfSIM which is an alliance of government, industry, and academia. The primary focus of AfSIM is aerodynamics and aeroacoustics, with the potential for growth in other disciplines. AfSIM promotes technical interchange and transfer to develop prediction methodology. AfSIM is a worthwhile initiative for the weapons integration community and is involving both U. S. and international weapons integration experts.

The role of the missile manufacturer in tactical missile/aircraft integration is the topic of **paper 25.** The paper describes the approach to integrating a Mica missile to the Mirage 2000-5 aircraft. The primary point of the paper is that the missile engineer is an essential team member when contemplating an integration program. The "force multiplier" requirement of a fighter, being able to simultaneously engage multiple targets, is the motivation for the integration. The conceptual studies, exploratory developments, and other necessary ingredients are briefly described, from the development of an indigenous microelectronics industry through the development of new displays and crewstations, with continued emphasis on the mechanical and electrical interfaces. A novel approach to integrating multiple simulation databases, missile and aircraft, is proposed as a way to reduce risk and necessary captive carriage and separation events. Technical integration issues such as missile launcher integration, radar avionics, transmission of information to the missile, aero-mechanical and electrical interface between the missile and aircraft, environmental considerations, and separation characteristics are but a short list of issues to be solved for successful integration. The author concludes by reiterating the necessity of including the missile engineer in the program team as early as the radar engineer and avionics engineer.

Paper 26 presents an interesting synopsis, history, and look to the future at the air to ground weapons aiming task. The authors provide an interesting and entertaining look at the history of weapons aiming from pre-WWI when the Germans threw bricks out of aircraft as weapons through the evolution of the head-up display to helmet mounted sights and helmet mounted display. The authors further present an interesting analysis of off-axis weapons delivery and automatic targeting systems. An informative discussion of rules of engagement (ROE) and weapons delivery in the recent world conflicts is provided plus a discussion of ground defenses against airborne weapon delivery. The paper concludes with automatic target recognition and target credibility with the modern digital cockpits.

- **ROUNDTABLE**

A roundtable discussion was held at the end of the symposium. The roundtable was led by Mr. Roger Detrick, Technical Program Chairman, and participants included the TER author, Robert A. Russell, Professor Nafiz Alemdaroglu, Turkey, Mr. Jim Papa, US, Dr. Peter Hamel, Germany, Mr. Roberts, UK, and Mr. Chivot, France. The TER author gave a brief synopsis of the symposium and closed

by using a block diagram from Mr. Taverna's paper 13 to emphasize how best to integrate flight testing, wind tunnel testing, and analysis with results from each being used to update and complement the other approach. Each participant gave a brief statement followed by questions and discussion with the audience participation. Key points mentioned are as follows:

- Turbulence is the challenge for Computational Fluid Dynamics
- There were few systems integration papers in the conference
- Four main points from RADM Chenevey's keynote address were mentioned along with the fact that the technical expertise is resident in "aging engineers".
- There were few papers discussing program management; should extend the Taverna triangle to include the acquisition community
- Aircraft manufacturers, weapons engineers, and users/operators need to come together early to ensure the best integrated weapon system is developed
- Largest improvement being made and still to be made in the computational techniques
- Instrumentation systems are becoming smaller
- Growing concern exists about the growing costs of integrating and clearing weapons from individual aircraft.
- Still more need exists for computational work
- Acoustics environment is hard to model using scaled models
- Some consideration to do an AGARDograph on weapons separation

• CONCLUSIONS

The third symposium of the Systems Concepts and Integration Panel is considered by this author to have been most successful. The goal of the symposium was to critically review the overall state-of-the-art in aircraft weapon system compatibility and integration and provide beneficial ideas for future development. The goal was achieved to a great extent because of the high quality of papers, the quality of the presentations, and the broad selection by the Technical Program Committee of the most relevant weapons integration information available in the late 1990's. Throughout the symposium there were well over 100 attendees at all sessions. The sharing of ideas and penetrating questions during the presentations as well as the open discussion at the ROUNDTABLE provided a constructive sharing of ideas that will help the weapons integration community into the future. It is obvious to this writer that there is still much work to do to effectively make use of all available tools, such as wind tunnel, CFD and other analysis techniques, and flight testing to reduce the cost and time of integration and clearance of weapons on tactical aircraft.

• RECOMMENDATIONS

Recommend the Systems Concepts and Integration Panel sponsor another weapons integration symposium in about four years to review progress being made in the various computational techniques and new instrumentation devices. As the NATO nations defense budgets continually shrink, it is imperative to make the weapons integration and clearance processes more efficient

thereby reducing costs and time for the clearance. A RTO sponsored symposium in four years will foster the sharing of new ideas within the weapons integration community.

NATO RTO System Concepts and Integration Panel

"Aircraft / Weapon System Compatibility And Integration" Symposium

Chester, UK, 28 Sept - 2 Oct 1998.

Opening Remarks

John Mabberley
Managing Director DERAtec
Room 2009, Cody Bldg, Ively Road
Farnborough, Hants GU14 OLX, UK

Monday 28th September, 0930-0935

Good morning. I'm John Mabberley, Managing Director of DERAtec - the part of the Defence Evaluation & Research Agency which focuses on international and commercial business partnerships. I also have the privilege of being one of the UK's National Delegates to NATO's Research and Technology Organisation.

As a member of this Board, I would like to welcome you to the UK, to this historic city of Chester and to this symposium on "Aircraft/Weapon System Compatibility and Integration". This symposium has been organised by the Systems Concepts and Integration Panel, one of the six panels of the RTO.

I am delighted we have more than 120 participants from the NATO nations here today. We particularly welcome participants from Poland, one of the Invited Nations at the RTO. I am also pleased we have representatives joining our symposium from Estonia and Lithuania, Partnership for Peace nations, and a guest participant from Australia (welcome to you all; welcome to our Summer!).

It also gives me great pleasure to welcome our Keynote Speakers, Admiral Chenevey, current head of the Weapons Division at the US Naval Air Warfare Centre and Dr Chris Pell, Director of Science (Air) from the MoD here in UK. I look forward to hearing your remarks in a few moments.

The RTO, formed as you know from the former AGARD and DRG, is a relatively new organisation within NATO, and is still evolving. All of those on the Board greatly appreciate the efforts made by you all in achieving such success in this transition. Such important events as this symposium are a valuable legacy from the former AGARD, but it is very much a model for the future of the new Panels.

The full SCI Panel will be meeting here later this week, to conceive and plan further new and worthwhile activities to foster research and technology within NATO and to take the Alliance into the new Century.
I have a personal passion about this organisation and what it might achieve, but that potential can only be realised if you all help us think about this future. In your deliberations, consider how the RTO work can complement and draw benefit from your national programmes. Decide how it fits in with other collaborative initiatives and forums. NATO RTO must never be just another source of science and technology funding, nor is it adequate for it to be just another networking forum (however good it is as just that). It <u>must</u> be a science & technology community which focuses on the <u>mission</u> of NATO and is seen to support that <u>role</u> not only in terms of shared technology but also by ensuring common standards, interoperability, transparent communications, shared logistics and training in preparation for an increasingly diverse range of future operations.

I have been given five minutes, and that was six of them! So I must end, but not without thanking on your behalf the principal UK organisers, Barry Tomlinson and Shelagh Martin, for making such splendid arrangements. I would also like to thank British Aerospace for hosting the Technical Tour on Thursday.
I wish you all a very stimulating and successful symposium.

I would now like to hand over to the Technical Programme Committee, in the person of Keith Hulme.

"THE CHALLENGE OF COMBAT SUPERIORITY THROUGH MODERNIZATION"

Rear Admiral J. V. Chenevey, USN
Assistant Commander for Logistics and Industrial Operations, Bldg 449
Naval Air Systems Command
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This morning I would like to spend a few minutes discussing a subject very near and dear to my heart — sustainment. I understand that there are several definitions to the word sustainment as it pertains to aviation. There's the logistic definition and under my present responsibilities in Naval Air Systems Command I deal with that specific connotation, as you would expect, everyday. Today though, I would like to address sustainment in a broader sense — that is, in the context of being able to sustain the strength of the aviation arms of our respective armed forces.

When I look at the budgets for the United States Armed Forces and focus on the procurement accounts, I have to wonder how we are going to sustain the requisite numbers of aircraft on our flight lines and aircraft carriers in the out years. Our mission is to be combat ready. That implies that we are not only highly trained, we are properly staffed with personnel and properly equipped. It's the properly equipped piece that I would like to focus on this morning. While my remarks reflect my own Naval Aviation forces, I suspect there aren't too many in this room who aren't faced with the same challenges.

As I mentioned, I'm concerned about having aircraft on the flight lines and carrier decks of the U.S. Navy ships. Certainly our procurement budgets in our current five year plan indicate that new production/new procurement of aircraft will not be of sufficient volume to replace the existing inventory as it ages and attrites. In fact, for the U. S. Navy, 85% of the aircraft we will take to a conflict in the year 2010 are already in our inventory.

The Navy has adopted various strategies for maintaining the viability of naval aviation. Recapitalizion is an obvious one. Under this strategy we would simply go out and buy new equipment and sidestep such issues as obsolescence, tired iron, rework, retrofit, etc. We would simply buy our way out of the current force mix to a new, more modern, more integrated mix. Sounds good and works fine assuming you have the enormous funds required to bank-roll the developments and procurements. Some level of recapitalization is necessary but to think we can solve the total sustainment problem this way is simply not realistic given the current and expected fiscal constraints. Certainly, for the limited number of new procurement programs we will have, we must develop faster processes by which we develop the

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requirement, deliver it to our contractors, build and test the hardware and software that is produced and deliver the finished produce in sufficient numbers to our warfighters. The development cycle is, as we all know very, very long and very costly. Along with our counterparts in the commercial aviation industry, we have made progress in the design, build and T&E processes. But, it appears to me, our progress is at a painfully slow pace. In the United States our acquisition agencies are working hard at reduction of the procurement cycle time. I've seen a lot of claims in all sectors of the market place proclaiming Better, Cheaper, Faster. My experience is that typically only two of those attributes are attained in the final product.

Since we will be unable to buy our way out of our aging platforms and weapons systems, we must rely more and more on modernization. Modernization is the process of updating the existing inventory to meet the current day and expected future threat. These modernization efforts include, structural upgrades, avionic upgrades, airframe rework and of course integration of newer generation weapon system components and the latest weaponry. The processes we employ to modernize are as important as those processes we use in procuring new aircraft. Many of the papers you will have delivered over the next few days will address techniques and processes for attaining a recapitalized and modernized fleet.

Modernization has some unique aspects to it. It typically provides new capability for the warfighter quicker than the design and manufacture of a new platform. It generally cost a lot less, so the capability being considered can be more wide-spread through out the forces. But in many ways it's much more difficult, as most of you know, than building from scratch. You are not starting with a clean sheet of paper. The constraints are real and most times unchangeable. Typically, there aren't as many avenues for trade-offs like you might find in a new design. Integrating current day weapons systems designed with up-to-date electrical and logical interfaces to a twenty year old aircraft is always a challenge.

So what does all this mean to you, as you look to modernize and recapitalize your own armed forces. It really all comes down to money. It really comes down to getting more out of the limited money our

services have for these activities. And it comes down to us as the leaders in the technical fields needing to do what we can to put less and less strain on the financial accounts to deliver the products our warfighters need to sustain their combat superiority. The money we don't need to complete today's projects will help fund the needed projects of tomorrow.

If I may jump now to another of my favorite subjects for just a couple minutes. One that I think you will appreciate in that it will be in large part the genesis of the money we need to modernize our aging aircraft. Affordability. There are two aspects to affordability. One is in the operations and support of our aircraft and the other involves a sort of "bang for the buck ratio" in the modernization efforts.

I have come to appreciate the affordability aspects of operating combat aircraft. At the Naval Air Systems Command we have been working hard to define the operations and support costs of our various Type/Model/Series aircraft. We have identified no less than 140 elements in the buildup of those costs. We now track 136 and are working to effect the highest costs elements in order to reduce the over all life cycle cost and to hence reduce the yearly operational funds needed to operate our aircraft. This isn't exactly a subject many of you have much interest in but you should understand that the money we need for reccapitalization and modernization will largely come from our ability to reduce the O&S accounts. So we in the U.S. Navy have a profound incentive to make a positive impact in this area. When you consider that the average age on our aircraft is nearly 15 years old, you can begin to imagine the challenges we have in reducing these costs.

The other aspect of affordability is one that you have more influence upon.

In the years since I served as the chief engineer on the F/A-18 program I have seen the cost and time to integrate weapons, avionics and functionality decrease significantly. There is still, however too much money and too much cycle time required but some progress has been made. I have asked for years why it costs so much to integrate a new capability onto the F/A-18. I know, understand and appreciate how we generate those large costs but also don't always understand why it is that we can't seem to reduce them.

Our dependency on Modeling and Simulation has increased - but it appears to me - only reluctantly. As engineers, we only grudgingly give way to new methods of testing and integration. The rigors we demand to certify our models are time consuming and expensive since we typically run our time proven methods in parallel with the new M&S techniques for what seems to me to be an inordinate amount of time. All well and good, but we must be more aggressive in stepping forward to accelerate the use of these tools if we are to contribute to our services ability to modernize and recap by reducing our appetite for those funds. Remember, the money we don't need to complete today's projects will help fund the needed projects of tomorrow. We need to continue to complete our tasks with safety in mind but we need also to sometimes step out of the comfort zone a bit — especially where there are big money savings and large reductions of cycle time.

A few years ago, as the Program Manage for Conventional Strike Weapons I had the great pleasure of having the Joint Standoff Weapon (JSOW) development as one of my responsibilities. In addition to all the challenges we had in developing a forty-mile glide weapon, was integrating it into most of the tactical aircraft in the U. S. Aviation inventory. I could go on for a long time in telling of our adventures in finding commonality among the many and varied applications of MILSTD 1760B but that's probably better left for another time.

One of the main challenges was separating and jettisoning a weapon like a JSOW from the very complex flow fields found around the F/A-18. While the JSOW only weighs about 1000# it has a relatively high volume. The density is quite low. Additionally, it is rather tall with respect to it's width. The consequence of this geometry and density is that for its' size, it responds very willingly to the surrounding flow field.

Prior to the JSOW separation testing, PAX River was doing work in photogrameterics. I hope I explain this correctly, but the premise of the technique is to photograph the actual missile separation in such a way that an accurate digital flight path can be generated. This then can be played against the six degree of

freedom models of the weapon. In the case of JSOW testing, if the two were identical, or nearly so, then we would begin to have confidence in the six DOF to predict future separation events.
As I mentioned earlier, we tend to run new techniques in parallel with old, tried and true methods. JSOW was no exception. In order to do the separation and jettison tests to develop the full envelope clearance, it was determined that it would require 24 test articles. We planned to collect photogrameteric data and analyze it as the tests continued but there seemed to be little enthusiasm for using the data to reduce the numbers of articles needed to complete the envelope testing. Without relating each test event to you, suffice to say that the photogrameteric data began to validate even in the earliest test events that the missile was behaving within a few percentage points of the 6DOF prediction. The engineering staff and I had more than one conversation about the need to begin to believe the 6DOF predictions and step over some of the test event so we could get to the end points earlier. Again, I'll leave out the details but at long last we did and in the end were able to complete a 24 article test with just 20 articles. Only a 16% reduction but really it was an elimination of 4 of the last 10 or so events so the overall reduction was fairly dramatic.

For the JSOW did this reduction represent a great savings? No. The 24 test articles were already purchased but the real savings were realized in the test data that didn't need to be reduced and analyzed and in the test range and test aircraft expenses not to mention the schedule time saved. Future programs ought to be the beneficiaries of the real program cost reductions. If I were to develop another weapon like JSOW I would stress the test community to complete the full envelope testing with 8 to 10 test articles. That would represent savings of millions of dollars and months of development time. Real savings that can be applied to developing more systems for modernization or used to purchase new platforms to replace an aging fleet.

No matter how good a modernization candidate is — if it's unaffordable to integrate or to maintain it likely will remain on the shelf. In fighter pilot terms — the opportunities to attack affordability issues in the processes of modernization and recapitalization represents a "bogey rich environment".

The challenges are in front of us. You here today, hold many of the keys to reduce development cycle time and reduce the integration cost of these new and sorely needed systems. We need to venture boldly but on a calculated path that gets us to where we are increasingly contributors not just to greater combat capability but to the overall sustainment and vitality of our combat aviation assets.

Exploitation of Technology for Military Advantage

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1. INTRODUCTION

For the last 200 years, the dominant force in international affairs has been the nation state, with most wars resulting from attempts to either create or expand such states. In contrast, over the next 20 years, the risks to international stability are likely to be more diverse and to include sources such as; ethnic and religious conflicts; population and environmental pressures; competition for scarce resources; drugs, terrorism and crime. These pressures operate both within states and across borders. The break up of states seems likely to be as much a security problem as traditional expansionism. Moreover, the consequences of initially local crises may well spread dramatically in an ever more interdependent world.

Although the potential threats to security are becoming more wide ranging, leading to uncertainty in the origin and nature of future conflicts, it is indisputable that technological developments will have a very significant impact both on the nature of the threats we face and our options for responding to them. Many of these developments will be double edged, bringing new vulnerabilities as well as opportunities. To benefit from such developments, the technologies must be available in a timely manner, at the lowest possible risk and, perhaps most importantly, at an affordable cost within a declining defence budget.

Aircraft and weapons are just two of many military systems that rely heavily on technology to provide an advantage over opposing forces.

2. MILITARY/TECHNICAL DRIVERS

Even if it ever transpired that Unmanned Air Vehicles (UAVs) took over all combat aircraft, attack helicopter, Stand-Off Missile (SOM) plus Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) roles, there would still be a need to carry and release weapons from platforms of some description. In response to the situation outlined in the introduction, the main military drivers for aircraft and weapons are mission effectiveness, in terms of survivability and lethality, and affordability, i.e. securing maximum effectiveness at minimum cost, together with flexibility.

Improvements to potentially hostile air defence systems necessitates commensurate improvements to survivability measures if attrition rates are to be minimised. A major contribution to this will be effected through the reduction of aircraft and/or weapon signature. The level of signature reduction required will depend, in part, on the balance between the aircraft and weapon range capabilities; a very stealthy, long range, SOM might reduce the stealth requirement for the aircraft. Greater precision in the delivery of weapons is required in order to increase lethality while minimising collateral damage. In order for an aircraft to have the flexibility to perform multiple roles, it must have the ability to carry a variety of existing and future weapons and to deploy them optimally and intelligently according to mission needs.

Translating the military drivers into technical terms identifies the main technical driver for aircraft/weapon integration as development of a capability to determine the optimum means of integrating weapons with an aircraft, by minimising aerodynamic and signature penalties, while ensuring that the weapons are released safely and satisfactorily. The issues associated with the integration of an aircraft and its weapons will be dealt with by breaking a mission down into three main phases; carriage, release and post-release.

3. CARRIAGE

Having produced a clean, aerodynamically efficient shape which is capable of at least impressing audiences at airshows with its speed and agility, the aircraft designer then finds that the military want to hang weapons off it. The flexibility requirement ensures that the number and type of weapons to be carried will be extensive and can be expected to increase during the operational life of the aircraft. Carrying eight Alarm missiles, an Electronic Counter Measures (ECM) pod and a chaff/flare dispenser under a Tornado has a significant impact on performance. Not only do the weapons add weight, they also increase drag. Increased drag results in reduced range, speed and agility. Unfortunately, the drag increment is not simply the sum of the drag of the isolated weapons. Unless great care is taken over the design of the installed configuration (e.g. pylon shape/position, weapon arrangement), aerodynamic interference effects between the aircraft, pylons and weapons can increase the total drag to a level significantly above the sum of the isolated components. The fact that the weapons payload will vary depending on the mission, and even on the various phases within a mission, just compounds the problem.

In addition to external weapons carriage increasing drag, it restricts the flight envelope due to flutter (a destructive interaction of unsteady aerodynamic forces with structural vibrations). As for the aerodynamic interference problem, the flutter problem is compounded by the wide range of required weapon payloads, each of which needs to obtain flight clearance before the military can use it in anger. At a less

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severe level, the effect of broadband noise generated by the aircraft/weapon configuration, and repeated exposure to high g manoeuvres, can result in surprisingly short weapon life times.

Having loaded the aircraft up with weapons and, as a result, reduced the performance of the aircraft and restricted the flight envelope, have the chances of reaching the weapon release point and returning safely been increased? Probably not but, on the other hand, without weapons, mission effectiveness is likely to be somewhat limited!

Signature control can improve survivability but brings with it a new set of problems. Yet again, the wide range of required weapons payloads compounds the problem. Potential techniques for low signature carriage include conformal shrouds, pylon/weapon shrouds and tube launched weapons. Evaluation of these solutions requires an accurate prediction of the signature which, for such complex configurations, is technically very challenging.

A possible alternative, or supplement, to myriad external carriage configurations is internal carriage. Financial constraints are likely to mean that any new aircraft utilising internal carriage will be expected to accommodate existing ('legacy') weapons. The size of the bomb bay will, therefore, be dependent on the size of these weapons. This is significant because the size of the bomb bay determines the size, and inter alia the cost, of the aircraft. Choice of bomb bay size also places a constraint on the size of future weapons. The incorporation of a bomb bay inevitably increases the size of the fuselage and hence increases drag. Unlike external carriage, however, release of the weapons from a bomb bay will not reduce this drag. Internal carriage also makes it harder to load and inspect the weapons, due to restricted access.

Prior to release, it may be necessary for the aircraft to communicate with the weapon in order to, for example, pass navigation and target data, prime the weapon or run-up the turbine. This requires compatibility of aircraft and weapon software and hardware, again bearing in mind the wide range of required weapons payloads. The issue of effective and commonly accepted interface standards between weapons and the launch platform is by no means trivial.

4. RELEASE

It is vitally important to have confidence that a weapon, when released from the aircraft, will follow a trajectory that ensures safe separation, i.e. the weapon separates from the aircraft and stays separated. There have been a number of occasions in the past where aircrew have been somewhat surprised to find themselves victims of their own weapons.

The aerodynamic behaviour of internally carried weapons is highly dependent on the bomb bay flowfield. The flowfield of an empty bomb bay is, in turn, highly dependent on the geometry of the bay, with the length to depth ratio being the most important factor but with the bay doors also having an influence. Shallow and deep bays are characterised by markedly different flows which lead to quite different types of problem from a release standpoint. Weapons in shallow bomb bays are subjected to large loads and moments. In particular, large pitching moments make weapons release difficult and can result in the weapon rising back into the bay and colliding with the aircraft. Although the problem is less severe for deep bays, release of weapons from an internal bay usually degrades the release trajectory relative to that from an external weapon location.

With the doors open, the bomb bay generates an extremely harsh unsteady pressure environment. The problem is more severe for deep bays than shallow bays. Deep bays can exhibit rms levels in excess of 170dB, with most of the energy concentrated into a small number of discrete frequencies. These levels are capable of damaging equipment within the weapon and causing structural damage to both weapon and aircraft.

Opening the bomb bay doors will significantly increase signature levels. Although door design can have an effect on the increase in signature, if a stealthy aircraft utilising internal carriage is to minimise the risk of being detected, it needs to be able to open the bomb bay doors, release the weapons and then close the doors quickly enough to ensure that the enemy radar cannot obtain a useful and meaningful detection.

Knowledge of the weapon trajectory is required not just to ensure a safe release but also to ensure a satisfactory release in terms of weapon effectiveness. A weapon that releases safely but ends up in an attitude such that it cannot recover in order to reach the target has zero mission effectiveness.

5. POST-RELEASE

Following release, maintaining a low signature can prove to be problematical for both internal and external carriage. For internal carriage the problem is one of resealing the bomb bay doors once the doors have been opened in flight. For external carriage, the issue is one of 'cleaning up' the pylons.

Communication between the weapon and the aircraft may still be required post-release so that the aircraft can provide the weapon with guidance information.

6. CURRENT TRENDS

The aerodynamics of weapons is becoming more complex as non-axisymmetric and stealthy shapes, often with complex fin and wing arrangements, become more common. These shapes are often unstable and it is far from certain that safe release can be achieved for external, let alone internal, carriage schemes. The deployment of aerodynamic control surfaces and/or active control of the weapon during release may improve the situation but, for internal carriage, these options may only be practical once the weapon has cleared the aircraft. As a result, it may be necessary to lower the weapon from the bay into the freestream before release. The devices used to lower the weapons will need to be structurally sound in the presence of a hostile bay flowfield. Aerodynamic stability may not be achieved until after the deployment of the stowed control and/or lifting surfaces.

Battle damage assessment is required in order to evaluate mission effectiveness. The benefits of SOMs are reduced if an aircraft has to overfly the target in order to assess the battle damage. This situation could be avoided if positional data could be transmitted by the SOM back to the release aircraft, or some other platform, to provide information on

whether or not the SOM had hit the target. It might also be possible for the SOM to release a sensor that would detect whether or not the SOM had detonated and transmit the information.

For those countries without the funds to procure specific weapons to attack specific targets, greater flexibility will be required, with a single weapon being capable of attacking a range of targets and being mounted on a range of aircraft. NATO Mil-Std-1760 facilitates the latter, with the standard covering both mechanical and electrical connections. Due to large amounts of hardware being produced prior to the introduction of 1760, equipment tends to be, at best, compatible with the standard rather than compliant, and this is likely to remain the case for some time. However, compliance offers the prize of interoperability between services and between nations.

7. CAPABILITIES

Regardless of the best efforts of the Synthetic Environment community, flight testing will remain the final arbiter of success in aircraft/weapon compatibility and integration. However, flight tests are costly and not without risk and so need to be kept to an absolute minimum.

Wind tunnel testing is an invaluable technique but the cost of transonic/supersonic testing is still considerable while scale effects can result in the model flowfield differing from that around the full-scale aircraft. Although wind tunnel testing is well established, new techniques, such as pressure sensitive paint, continue to be developed and techniques for obtaining more detailed field data would be of value.

Although Computational Fluid Dynamics (CFD) has made considerable progress over the last three decades, the flows associated with weapons carriage and release can be so complex that there is plenty of scope for further improvement. CFD complements wind tunnel testing by increasing the number of design options that can be considered before committing to the manufacture of a wind tunnel model. CFD can provide detailed information for a small number of configurations which can then be tested in a wind tunnel to provide information, albeit less detailed than from CFD, over a much larger proportion of the flight envelope. Different CFD methods will be most appropriate for different aspects of aircraft/weapon integration and so development needs to take place across a broad spectrum of methods.

Low signature is a fairly recent requirement and so, not surprisingly, signature prediction methods are relatively immature. However, further development is needed for aerodynamic/signature trade-offs to be assessed as early as possible in the design process.

8. THE WAY FORWARD

Aircraft/weapon integration is a highly complex, multi-disciplinary process where success can be highly beneficial but where mistakes can be very costly. If the optimum balance between mission effectiveness and affordability is to be achieved, a 'total systems' approach offers the best way forward. 'Smart procurement' is likely to lead to standardisation, ideally across all NATO nations, of aircraft/weapon interfaces in order to ensure interoperability, both between services and between nations, and affordability. A wide variety of technical challenges have been identified that need to be overcome before the military drivers can be satisfied. This symposium addresses these challenges and will, hopefully, demonstrate significant progress in many areas. As the potential threats to security continue to evolve, additional challenges are likely to arise, ensuring that aircraft/weapon integration remains a thriving technology area where innovation and vigour will reap rich rewards.

ACFD APPLICATIONS TO PREDICTING STORE TRAJECTORIES

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1. SUMMARY

ACFD (Applied Computational Fluid Dynamics) is a tri-service project which has the purpose of verifying Computational Fluid Dynamics (CFD) tools for use by the aircraft-store certification organizations. The project is part of the Test Technology Development and Demonstration (TTD&D) program, which is funded by the Office of the Secretary of Defense (OSD) Central Test and Evaluation Investment Program (CTEIP). During the past several years, several CFD codes have been evaluated for their ability to predict store loads in aircraft flowfields at transonic speeds. The paper presents the latest results of these evaluations for store external carriage loads and trajectory predictions.

2. LIST OF SYMBOLS

BL: Aircraft Buttline positive outboard, in.
C_l: Rolling moment coefficient, rt wing down
C_m: Pitching moment coefficient, nose up
C_n: Yawing moment coefficient , nose right
FS: Aircraft Fuselage Station, positive aft, in.
M: Mach number
P: Store roll rate positive rt wing down
Q: Store pitch rate, positive nose up
R: Store yaw rate, positive nose right
PHI: Store roll angle positive rt wing down. deg.
PSI: Store yaw angle, positive nose right, deg.
THE: Store pitch angle positive nose up, deg.
WL: Aircraft Waterline, positive up, in.
Z: Store C.G. location, positive down, ft.
α: Angle of attack, deg.
α_ι : Upwash angle, positive up, deg.
δ_ι: Sidewash angle, positive outboard, deg.

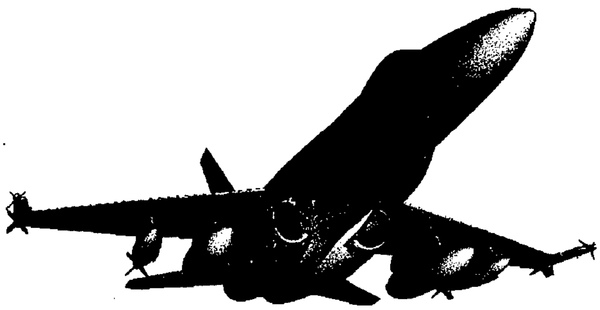
! Head, Store Separation Branch. Asso Fellow, AIAA.

3. INTRODUCTION

For CFD to be useful to a store separation flight test program the tool that is used must be able to provide reliable answers in a matter of hours or days. At the present time only panel methods that solve the linearized potential flow equations have this capability. The Navy has successfully employed potential flow techniques[1] to provide aircraft flowfield information in a qualitative sense. Unfortunately, these codes are not usable at transonic speeds, where most store separation problems occur. Although higher order methods (Euler and Navier Stokes) may have the potential to provide the correct answers at transonic speeds, at the present time these solutions may not be achieved until after the flight test program is completed.

The goal of the ACFD project is to provide the store separation engineer with a reliable CFD tool that can provide answers in times comparable to panel methods at transonic speeds. In 1996 the ACFD project funded several efforts to evaluate the ability of six different CFD codes to predict the flowfield for a generic store in the presence of the F-16 aircraft. The results[2-7] of these efforts were presented at an invited session at the AIAA Applied Aerodynamics Conference in 1996. Based on these evaluations, it was decided that one of these codes[2] appeared superior to the others in providing answers at transonic speeds in a reasonable amount of time. This code was selected to further evaluate its ability to actually quantitatively predict store trajectories by comparing to both wind tunnel and flight test data. This effort was conducted by the Navy, and the test case used was the JDAM on the F-18 outboard wing pylon and a 330 gallon fuel tank on the inboard pylon.

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.



F/A-18/JDAM CONFIGURATION

4. FLIGHT TEST RESULTS

For the F-18/JDAM the wind tunnel data predicted an anomaly in the aircraft flowfield. The aerodynamic coefficients decreased from M = 0.80 to M = 0.90, and then suddenly increased. This result was actually confirmed by the flight test results[8]. As may be seen in Figures 1 and 2, the trajectory for the clean aircraft with the store on the inboard pylon at M = 0.90 was more benign than that at M = 0.82. Since the dynamic pressure increased by 20% at the higher Mach number, if the aerodynamic moments were the same, the pitch attitude at M = 0.90 should have been at least 5 degrees larger.

PREDICTION USING GRID AND CARRIAGE DATA
F/A-18 M = 0.82 H=5000' BL = 88

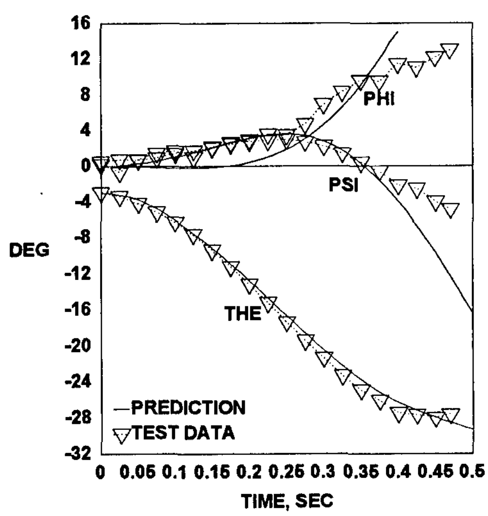


FIGURE 1 JDAM JETTISON COMPARISON

PREDICTION USING GRID AND CARRIAGE DATA
F/A-18 M= 0.896 H=4624' BL = 88

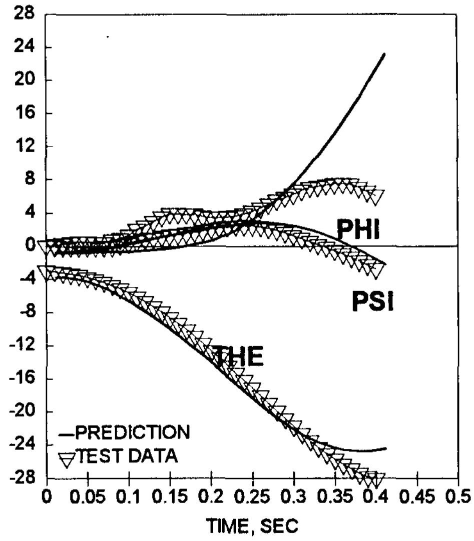


FIGURE 2 JDAM JETTISON COMPARISON

5. WIND TUNNEL TEST DATA

Both Captive Trajectory System (CTS) grid data, and store aerodynamic force and moment data measured on the wing pylon were available for this aircraft configuration (Config 1). When these data were input into a six-degree-of-freedom trajectory code, an excellent match with the flight test was achieved. This indicates that the wind tunnel test data accurately matched the flight test conditions. When carriage loads data were not used the trajectory predictions were[1] in much poorer agreement with the flight test results.

An explanation of the flight test behavior can be deduced by examining the store grid loads at these two Mach numbers. As may be seen in Figures 3 and 4, the pitching moment for the same aircraft configuration for this store at carriage actually decreases at M = 0.90 by 20%. The yawing moment is of similar magnitude for both Mach numbers. Only comparisons for moments are shown, since these have the principal impact on the trajectory.

F/A-18 ALPHA = 0
H = 5000' CONFIG-1 FLAPS = 0/0

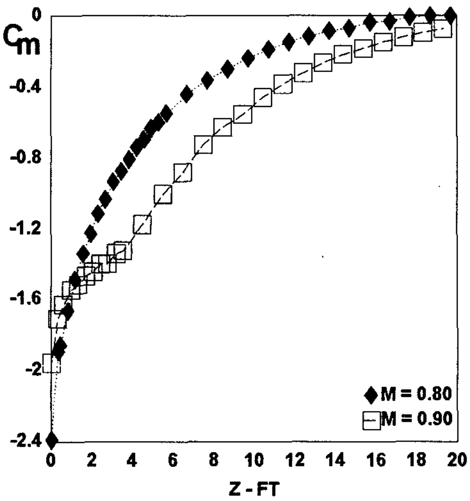


FIGURE 3 JDAM GRID COMPARISON

F/A-18 ALPHA = 0
H = 5000' CONFIG-1 FLAPS = 0/0

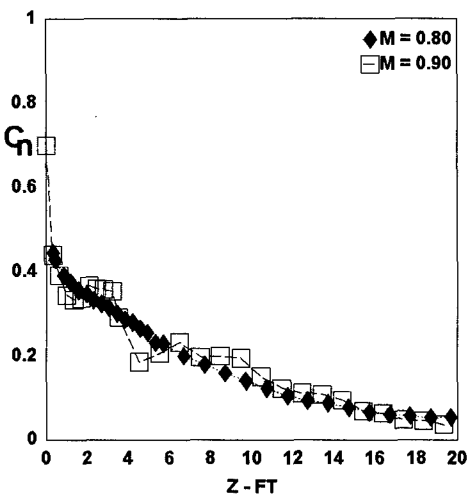


FIGURE 4 JDAM GRID COMPARISON

In an effort to better understand this behavior, wind tunnel test data for other stores for the F-18 configuration with a fuel tank on the inboard pylon and the store on the outboard pylon were examined. These data were selected because they exhibited the most severe variation with Mach number. Figures 5 and 6 show the change in moments for the JDAM, MK-84 and SLAMER stores with Mach number. The MK-84 and JDAM are both of similar size and shape; their behavior shows similar trends: a decrease in moments from M = 0.8 to M = 0.9, followed by a sudden increase. Note that this behavior is store dependent, since the SLAMER (a longer store) acts differently; it's pitching moment decreases with Mach number, while the yawing moment increases. For CFD to be a useful tool for store separation, it must be able to predict, at least qualitatively, this type of behavior.

STORE OUTBOARD, FUEL TANK INBOARD

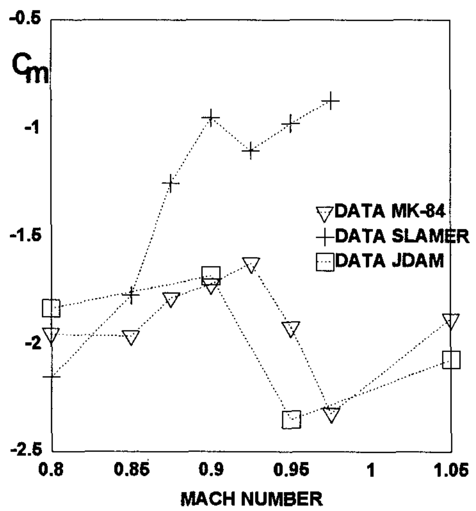


FIGURE 5 MACH EFFECT ON PITCHING MOMENT

STORE OUTBOARD, FUEL TANK

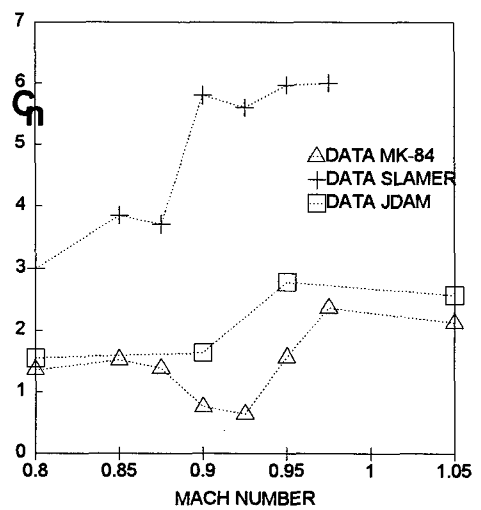


FIGURE 6 MACH EFFECT ON YAWING MOMENT

6. SPLITFLOW RESULTS

An attempt was made to see if the SPLITFLOW code could predict the sudden change in pitching and yawing moments seen in both the wind tunnel and flight test data.

A SPLITFLOW model was developed of F-18 aircraft with a 330 gallon tank on the inboard pylon and JDAM outboard.

SPLITFLOW is a Cartesian-based, unstructured, adaptive Euler/Navier-Stokes solver. The Cartesian approach generates cube-shaped cells that are aligned with the Cartesian coordinate axes. Grid refinement involves recursively sub-dividing each cell into eight cells which become "children" to the initial cell. Boundary geometry is defined by triangular faces, or facets. At boundaries, cells are "cut" to account for volume and flux changes. This feature allows SPLITFLOW to handle extremely complex geometries, and little care need be taken by the user to prepare or maintain the grid. Initial grid cell sizes are scaled from geometry facet sizes and are then refined or derefined, at specified iteration intervals, by the solver based on the user's choice of gradient adaptation functions (Mach number, pressure, etc.). The derefinement process uses statistical methods to look for low-gradient regions in the flowfield from which to remove cells, thus reducing grid density and computational requirements. The derefinement process is limited by a grid smoothing algorithm which requires adjacent cells to be no more than one "generation" apart. Further, cells are deleted by groups of eight only if all of the child cells in that group are flagged for derefinement. This is done to maintain the data structure. The refinement process follows, also applying statistical methods, and searches for high gradients to determine where cells need to be added. Since the code is "smart" enough to place cells where they are needed, the best initial grid is usually sparse and the flowfield is used to determine where new cells should be placed. With a sparse initial grid, flowfield information can propagate in fewer iterations, each of which take less time because there are fewer cells. For example, the original grid, which was limited to 800,000 cells, was appropriately initialized by slightly more than 100,000 cells.

Another benefit of cutting boundary cells is that geometry changes can be made easily while salvaging a developed solution. For example, if the user has a converged solution of an aircraft with undeflected control surfaces, a new geometry model with deflected control surfaces can simply be substituted.

Originally, the F-18/JDAM was constrained to 800,000 grid cells. The SPLITFLOW model was run on an SGI ONYX which limited the size of the problem. For 800,000 Cartesian cells, using four processors, one case (e.g. one Mach number and aircraft angle of attack) took 167 hours for 2000 iterations.

As may be seen in Figures 7 and 8, SPLITFLOW considerably overpredicted the JDAM carriage pitching and yawing moments at Mach numbers less than 0.95. For the subsonic Mach numbers the solutions were not converged even after 2000 iterations. This was due to the fact that the shock interaction between the store and the adjacent fuel tank was continually refined and it's location kept changing.

The solutions at the higher transonic Mach numbers (M>0.925), as well as at the supersonic Mach numbers were well behaved and converged in 1000 iterations. The predictions at the higher Mach numbers were in closer agreement with the wind tunnel test data.

Since one of the purposes of the study was to determine the minimum time required to obtain a reasonable solution, the F-18/JDAM was rerun using 300,000 Cartesian cells at the same Mach numbers. For 300,000 Cartesian cells 2000 iterations took 93 hours on one processor.

As may be seen from Figures 7 and 8, the solutions using the reduced number of grid cells appeared to be in better agreement with the test data at M = 0.90. This can be attributed to the code's fortuitous inability to over-refine the shock location, since the solutions at the supersonic Mach numbers were much worse. SPLITFLOW also still considerably overpredicted the pitching and yawing moments at the lower Mach numbers. It appears that the code might be generating a subsonic shock that in real life would be dissipated by viscous forces. Since the solution for 800,000 cells was better

than for 300,000, solutions for 1,5000,000 cells, as well as a viscous case, are planned.

F-18/JDAM BL 134.3 WL 70

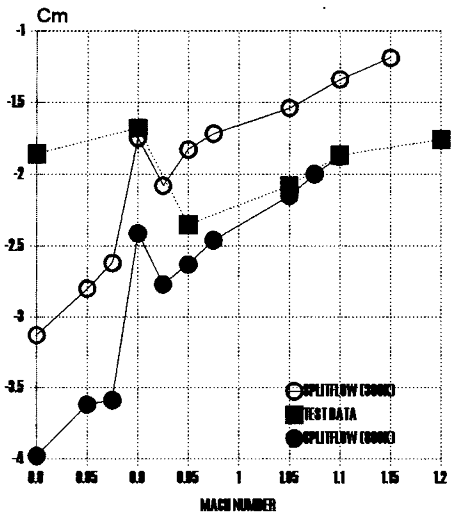


FIGURE 7 MACH EFFECT ON PITCHING MOMENT

F-18/JDAM BL 134.3 WL 70

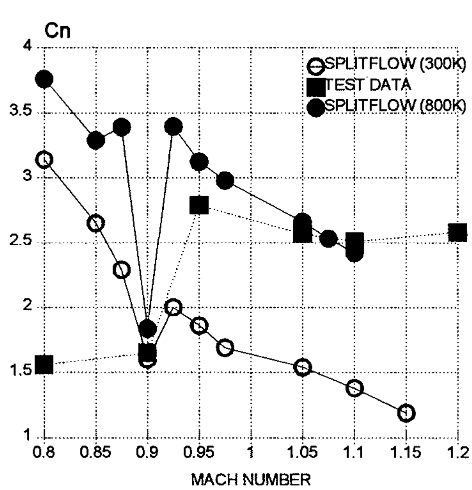


FIGURE 8 MACH EFFECT ON YAWING MOMENT

These comparisons will have to be done on a supercomputer, since the SGI workstation that we use has a storage capacity that limits the job size to 800,000 cells.

The forces were generally in better agreement with the test data than were the moments, Figure 9. This behavior has been previously noted, and can be attributed to the fact that forces, unlike moments, are not significantly affected by shock location. The correlation for the 300,000 cell case was significantly worse than for 800,000, Figure 10.

F-18/JDAM 800K CELLS

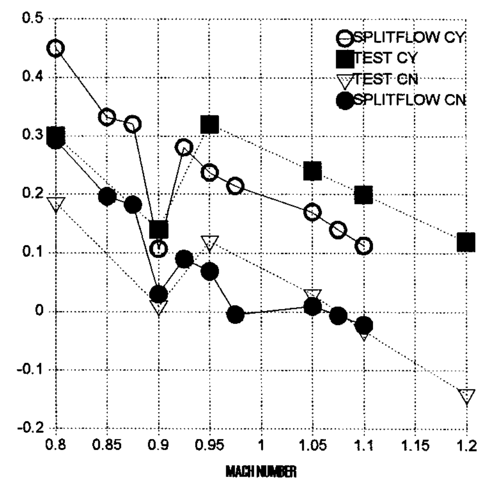


FIGURE 9 MACH EFFECT ON FORCES

F-18/JDAM 300K CELLS

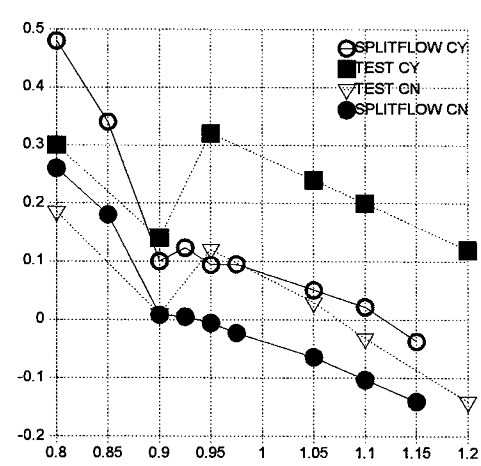


FIGURE 10 MACH EFFECT ON FORCES

7. TRAJECTORY PREDICTIONS

An indication of the trajectory errors that incorrect aerodynamic carriage loads can

lead to may be seen in Figures 11 and 12. In both cases the 300,000 cell SPLITFLOW predicted carriage loads and moments from Figures 7 through 10 were used, in conjunction with wind tunnel JDAM freestream test data and the IFM[1] technique, to predict the trajectories at Mach 0.8 and 0.9. The 300,000 cell case was selected because the carriage predictions were in closer agreement for the subsonic cases.

The JDAM trajectories at the lower Mach number totally overpredict the pitch and yaw motion, and would be useless in planning a flight test program, Figure 11.

F/A-18 M = 0.816 H = 4996'

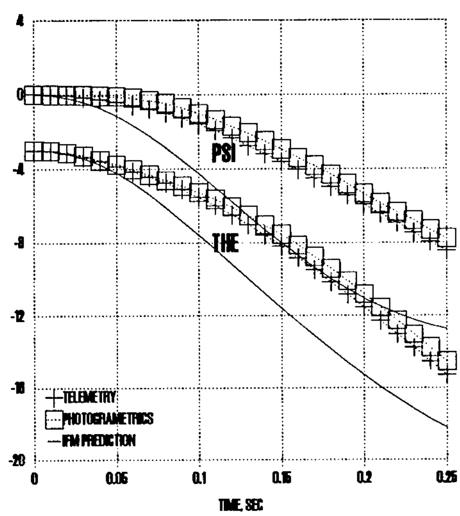


FIGURE 11 JDAM JETTISON COMPARISON

For M = 0.90, the SPLITFLOW carriage load prediction was in much closer agreement with the test data. As may be seen in Figure 12, the predicted trajectory is in good agreement with the flight test data. Obviously, if the carriage loads can be accurately predicted, there is a good chance that the flight test trajectories can also be matched.

F/A-18 M = 0.895 H = 4693'

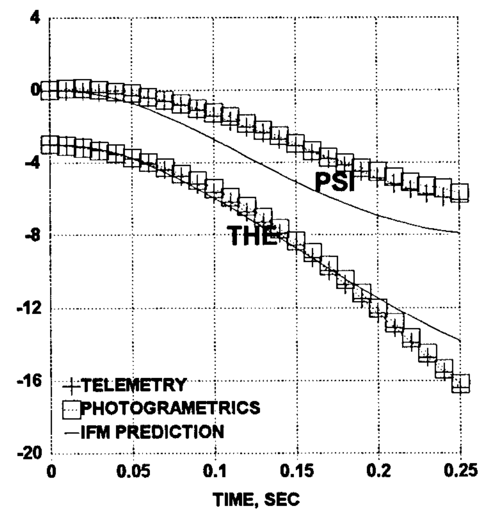


FIGURE 12 JDAM JETTISON COMPARISON

8. CFD CHALLANGE

Over the past several years there have been two notable organized efforts to validate, demonstrate and accelerate the insertion of CFD methods into the store certification processes for external stores carriage and release. These efforts have been documented in AIAA conference proceedings. These were the F-16/Generic Finned Store[3-8] and the Generic Wing/Pylon/Finned Store[9-17] test cases.

Many important lessons were learned; however, neither experimental test case included flight test data ("real" store trajectories). Because of this limitation, store certification engineers continue to express skepticism towards the accuracy of CFD methods. Also, the CFD community raised concerns about the credibility of portions of the wind tunnel test data, criticizing scale, model support interference, and wall effects. Therefore, there is a desire within the ACFD[18] program to reconcile these issues by conducting additional analysis by using a data set that includes both wind tunnel and flight test data.

8.1 SELECTION OF TEST CASE

Both wind tunnel and flight test data exist for the F/A-18C JDAM configuration as a result of a recent Navy store certification effort. During the flight test phase, photogrametrics and telemetry were used to track the position of the store during releases. Out of these tests, two release conditions were selected for this CFD Challenge. The basis for these two cases included the following considerations: 1) matching aircraft and store geometry in both wind tunnel and flight tests, 2) correlation between wind tunnel data and flight test data, 3) possession of both high transonic and low supersonic cases with interesting miss distance time histories, 4) ability to publicly release the wind tunnel and flight test data to an international audience.

8.2 TEST CASE PARAMETERS

The test cases selected were for M = 0.962 at 6,332 ft, and M = 1.05 at 10,832 ft. Both cases were for aircraft in a 45 degree dive.

For these two test cases, the configuration geometry for the wind tunnel and flight test are nearly identical. The only notable differences are: 1) the wing tip station in the wind tunnel test had an AIM-9 and 2) the armpit station in the wind tunnel test had an AIM-7. However, the 6DOF trajectory predictions using the wind tunnel derived pylon mounted carriage loads matched the flight test trajectories for these two cases. Therefore, based on these analysis the wind tunnel derived carriage loads are expected to correlate well with the flight test trajectories, in spite the two above discrepancies and other test issues such as scale, model support interference and wall effects for this Challenge.

9. FLIGHT TEST RESULTS

9.1 TEST FLIGHT #13

Flight test #13 was conducted on July 10, 1996. The store was released in a 43 degree dive at 6,382 ft. at M = 0.692.

The roll, pitch and yaw angles both for the telemetry and photogrametrics results are shown in Figure 13. They pitch results are in good agreement with each other, but the yaw and roll attitudes show substantial dissagrement.

The roll, pitch and yaw rates are shown in Figure 14. They are all in very good agreement with each other, especially considering that the photogrametric results are arrived at by differentiating the store attitudes.

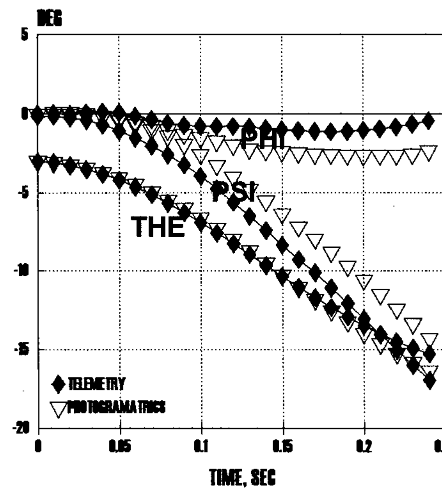


FIGURE 13 JDAM ATTITUDES

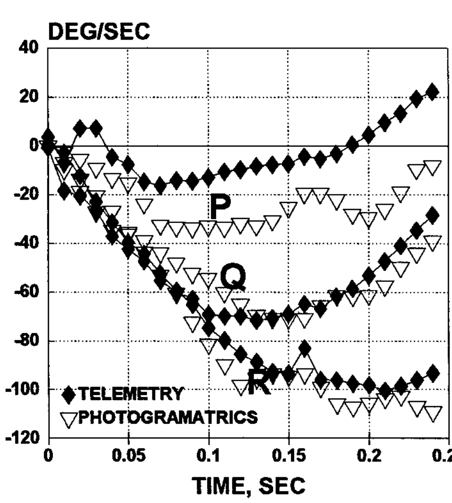


FIGURE 14 JDAM RATES

The photogrametric roll rates are somewhat larger than those measured by the telemetry package in the store. Since the telemetry roll rates are only for the store, while

those derived from the photogrametric data include aircraft motion, it appears that the discrepancy in store attitudes can be attributed to aircraft roll induced by the impulse imparted by the ejector force during the ejector stroke.

9.2 TEST FLIGHT #14

Flight test #14 was conducted on August 29, 1996. The store was released in a 44 degree dive at 10,832 ft. at M = 1.055

As may be seen in Figure 15, the pitch and yaw angles are in good agreement with each other. The photogrametric roll angle is much larger than that shown from the integrated telemetry..

The Navy is working on a method to incorporate the aircraft motion into trajectory simulations.

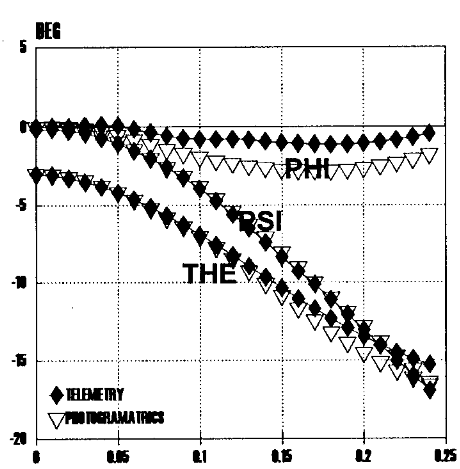


FIGURE 15 JDAM ATTITUDES

The roll, pitch and yaw rates are shown in Figure 16. The pitch and yaw rates are in very good agreement with each other. The discrepancy in roll rates can be attributed to aircraft motion, since the maximum difference occurs at 0.07 sec, which corresponds to the end of the ejector stroke.

In general, given a choice between telemetry and photogrametric data, the Navy prefers telemetry data. The store rates, and therefore the attitudes, which are integrated from the rates, are almost always a better indicator of the true store motion. Furthermore, in over forty test flights were both methods were used, the telemetry data was always usable, while in at least ten of the flights the photogrametric data was either unusable, or suspect. The only photogrametric data that is considered better than telemetry is that for the vertical displacement of the store.

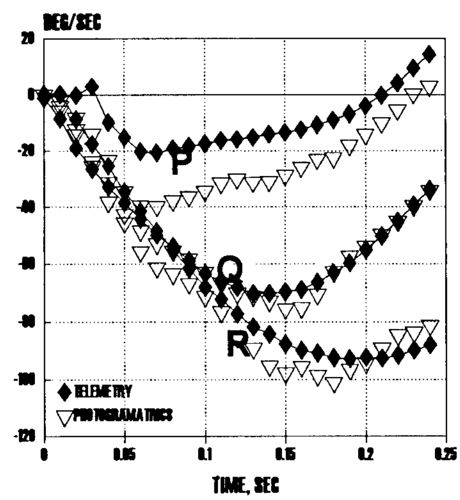


FIGURE 16 JDAM RATES

10. TRAJECTORY PREDICTIONS

Both Captive Trajectory System (CTS) grid data, and store aerodynamic force and moment data measured on the wing pylon were available for this aircraft configuration. These data were input into a six-degree-of-freedom trajectory code before the flight tests were performed. Parametric variations on flight conditions and store aerodynamic forces were performed to ensure that the flight test could be safely accomplished. After the flight tests were completed, the trajectory simulations were again performed, with the actual flight conditions used to try to match the flight test results.

As may be seen in Figure 17, the predicted pitch and yaw attitudes at M = 0.962 were in excellent agreement with the flight test results. The roll attitude was not well predicted. However, roll attitude, which is the hardest to predict, fortunately has a minimal impact on the trajectory. The photogrametric results are not shown, since they are considered to be less ac-

curate than the telemetery data.

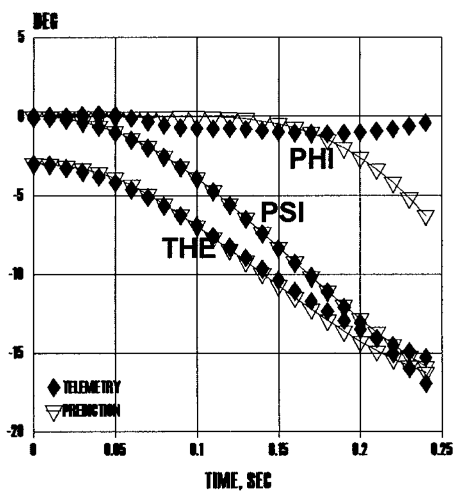


FIGURE 17 JDAM ATTITUDES

The flight test pitch and yaw attitudes were again in excellent agreement with the predictions at M = 1.055, Figure 18.

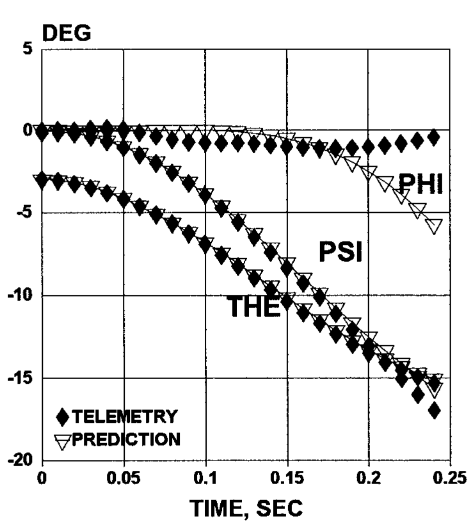


FIGURE 18 JDAM TRAJECTORY

11. CONCLUSIONS

It is clear that at the present time CFD can not be expected to accurately provide a good estimate of store carriage loads and trajectories in a reasonable time frame. Although SPLITFLOW initially seemed promising, it appears that a large number of cells (meaning solution times on the order of months on a workstation) may be needed to achieve a convergent Euler solution. The code may have to be run using the Navier Stokes formulation to achieve the necessary convergence at subsonic speeds. The Navy plans to use SPLITFLOW with 1,5000,000 cells to take part in the CFD challenge next year.

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An Automated Method of Analysing Store trajectory Simulations

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1. SUMMARY

The use of 6 degree of freedom numerical methods for the simulation of store separation from combat aircraft is now widespread throughout the world. The simulations are usually validated against a limited set of flight trials and then the numerical models used to assess the store separation behaviour throughout the proposed release or jettison envelope. This method has the advantage that many tolerance conditions and 'what if' scenarios such as failure conditions can be studied safely and cost effectively.

The simulations generally produce text output and graph plots of results for each case and often a trajectory 'picture' showing the store motion relative to the parent aircraft. Release cases are often time consuming to set up and even more time consuming to assess, especially as many tabulations or trajectory plots / graphical results have to be considered.

At British Aerospace Military Aircraft a simulation tool has been developed that allows models of high fidelity and accuracy to be created using a range of simulation techniques. The models can be created and executed using a graphical user interface and trajectories visualised in a 3D animation. An overview of the toolset known as STARS will be given in this paper.

However, the real strength of the STARS system is the ability to run all the required tolerance cases in a batch mode with a range of post processing tools for automated analysis of the results. It is this ability that is the main focus of this paper.

2. AN OVERVIEW OF STARS

STARS is not a 6 dof program but a toolset that allows an executable 6 dof model to be created to simulate a particular store's separation behavior **(fig 1)**. This makes the tool extremely versatile.

The core is a set of 6dof executable library objects using 4th order Runge-Kutta integration of body motion, including any change of mass effects, to which new equations can be added as either user Fortran subroutines or a series of type block text inputs **(fig 2)**. These text blocks are then translated into Fortran and compiled into an object set that can then be linked to the library to generate an executable model. These can be equations to simulate a missile autopilot for example using transfer functions that are integrated with the store motion.

A more specialised version of this code creation package allows the simple generation of the contraints and mechanics of release devices such as rail launchers, though usual ERU, rail and hook packages are already set up for the user.

In addition, objects that allow semi-empirical estimation of store loads in a flowfield (the NUFA code by BAe SRC) or calculation of the ERU gas dynamics or an aerodynamic tow cable can be linked into the system.

Data can be stored in self contained data structures (Data Arrays) of up to 5 dimensions. These can be a function of new or user created variables or variables declared as dependent variables from other data arrays. The results of data array interpolation can themselves be post multiplied by any other variable or constant value. This can create a complex data web of inter-relations **(fig 3)**.

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

The aircraft motion can be created from a set of idealised motion equations for straight flight with climb/dive, pull ups, banked turns or ideal 1g rolls or barrel rolls under 'g'. More complex aircraft motion can be imported from aircraft simulation software or actual flight data.

A flowfield data array can be selected from a database that describes the flow velocities around the aircraft at specific flight conditions. This can be wind tunnel measured or CFD generated. The store isolated aerodynamics can be defined as a series of components at up to 10 reference positions, each of which will read a local flow angle from the flowfield **(fig 4)**.

Grid loads data arrays can be defined which can be applied directly, or an interference array calculated from the grid loads and isolated aerodynamics in the flowfield at the grid conditions and positions. The grid loads or interference load can be factored by user defined decay laws as the store leaves the aircraft.

To guide the user and enable easier data input a graphical user interface (GUI) supports the whole system **(fig 5)**.

The STARS system can be configured to run multiple models in parallel for bomb ripple release/ store capture simulation, where interstore effects are approximated using an aerodynamic interference data array superposition technique based on relative positional and orientational effects.

Recently the ability to use Euler/N-S CFD methods to calculate the store aerodynamics during the store trajectory has also been developed.

The output of a simulation can be time history listings or graphs of any variable or in the form of a 3D animation from any user defined viewpoint **(fig 6)**.

The STARS system provides an extremely powerful , versatile and relatively accurate tool for trajectory simulation. However, NO simulation is perfect, as all depend on modelling assumptions and quality of input data. The way to mitigate this is to understand the sensitivity of trajectories to tolerance conditions and ultimate aircraft safety may require assessment of 'what if' failure conditions. This requires many cases to be simulated.

Of course it can be very time consuming setting up cases and then viewing the images and printing the pictures. Even more time can be spent assessing all the resulting images for trends and criticalities.

For this reason the automated run and analysis facilities in STARS which are the focus of this paper were created. These consist of ;-

1) An automatching tool to tune a model to match flight trials data.

2) A batch run system.

3) A collision and minimum distance monitor.

4) A scatter analysis post processing tool.

3. THE AUTOMATCHING TOOL

The automatching facility can tune the model to match a particular flight trial result by varying up to 50 input parameters of a model simultaneously.

The user can define any of the input variables from STARS and the variation range can be set to vary within predefined limits. Any number of output variable time histories can be assessed against equivalent flight data curves and curves can be weighted in importance by the user. The flight data points within a particular variable time history can be individually weighted or a weight function set on the time history e.g linearly reduce importance of data with time **(fig 7)**.

The facility works by determining an 'acceptability' value for the total output variable time history set and systematically adjusts the input set to minimise this value.

Unlike aircraft flight mechanics parameter identification codes this system has to work with comparitively poor data as store trajectories are generally derived from film analysis with no derivable data redundancy. Also the aerodynamics and mechanics of a store separation event is much more complex than an aircraft in free air. As might be expected the facility can sometimes have difficulty achieving an acceptable match and may require careful adjustment of all the

weightings. However for these situations manual matching can be equally problematic. A typical result can be seen in **fig 8**.

The process can be slow, requiring an hour for fairly simple cases. The main advantage is that it frees the user from a mundane job and can be running overnight if necessary to leverage the engineers working time. The tool also removes the user subjectivity and so gives consistent results between flight data sets.

4. THE BATCH RUN SYSTEM

The batch run system allows a set of cases to be executed from inputs defined in a simple text file for 3 different modes e.g **fig 9**. In each mode up to 50 input variables may be changed. The modes are random, list or grid. Random mode allows a number of cases to be run with a range specified for each variable within which a random value will be selected for each case. List mode allows a set of cases to be predefined as a list, whereas grid mode requires a series of values to be defined for each variable and cases are run for each combination of variable values.

A flowfield database and wildcard specification can be defined so that appropriate flowfields are selected automatically for each case submitted. Also a trim database can be defined which enables the correct aircraft incidence to be calculated for the aircraft flight conditions required in a particualr configuration. In addition a unix shell script can be executed after each case if required for auxilliary calculations.

Any input can be specified, such as incremental free air store pitch coefficients, new user defined variables, store mass, thrusts, aircraft flight conditions, aircraft manouevre. Some models can execute over two thousand cases in an overnight run.

Of course this means there are a lot of cases to assess in the morning!.

5. THE SCATTER ANALYSIS TOOL

To automate the analysis of batch run data the scatter analysis tool was developed. The code scans through a STARS time history file of user defined output variables and selects / interpolates to a time point which meets the criteria specified by the user. That point data is then appended to a file and identified by run number. By running this as part of the auxiliary script of the batch system or within a unix shell script to read all the output files created for the model, the scatter files are built up. The files can then be plotted as scatter graphs to show the data trends e.g **fig 10**.

The user criteria can be such things as ;-

- last time value or specified time
- max or min value of a variable
- largest peak or trough
- selected variable trigger value

  etc

Some of these criteria are explained in **fig 11**. Multiple critera can be defined as each creates its own scatter file. A total picture of the store's separation behaviour including sensitivity to tolerances can be easily developed, especially in combination with the collision monitor tool.

6. THE COLLISION MONITOR - CRASH

The CRASH program is a 3D collision and minimum distance monitor. It uses the same file structure as the animation program (**fig 12**) to determine the true 3D distance between requested geometries (or all if none specified) for each output time point of a simulation case within a user defined time range. A fast recursive cube volume subdivision algorithm is used to rapidly home in on the closest regions of geometries and thereafter the distance of nodes, lines and panels in the regions are checked. The code is also 'parallelised' such that the time history can be subdivided over several CPU's in the unix network. Output can be in the form of a summary file (giving minimum distance, time it occured, between which geometries and xyz location on those geometries), or a text file (**fig 13**) with this information for every time point. A plot file with minimum distance time history can also be created (**fig 14**).

Using unix scripts the summary data can be grabbed and pasted into the scatter analysis files for each case run in batch.

7. CONCLUSION

The STARS 6 dof modelling system is a powerful simulation tool with a range of techniques available for stores separation simulation. The models allow many tolerance conditions and 'what if' scenarios such as failure conditions to be studied safely and cost effectively. The many cases required can be run in a batch mode and analysed in a semi automatic manner.

The high degree of automation in the clearance process not only improves efficiency in that the engineers time is leveraged, but also gives a more complete picture of store separation behaviour.
This in turn results in more focussed flight trials and possible reduction in flight trials required.

Figure 1

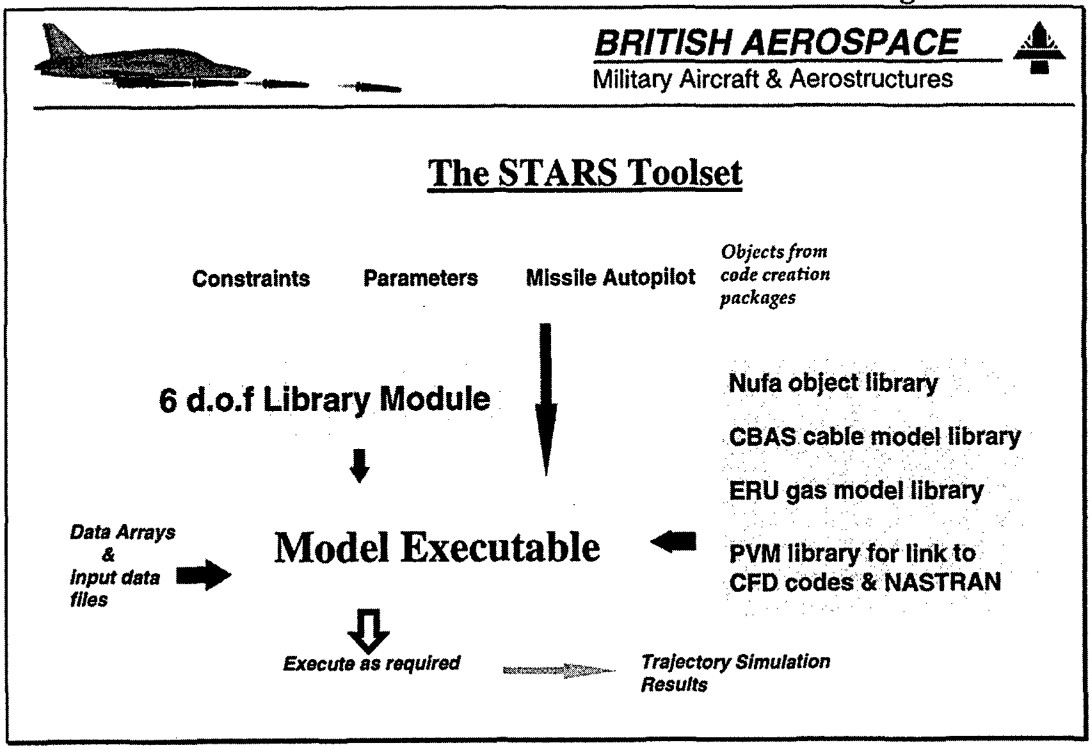

Figure 2

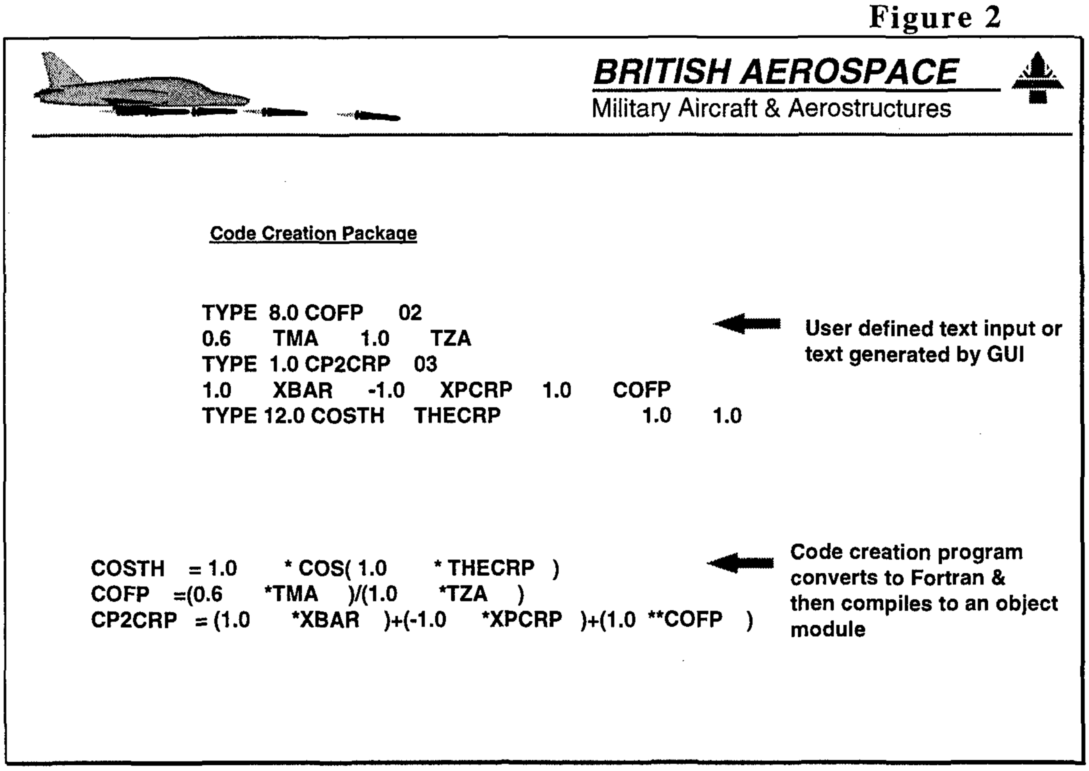

Figure 3

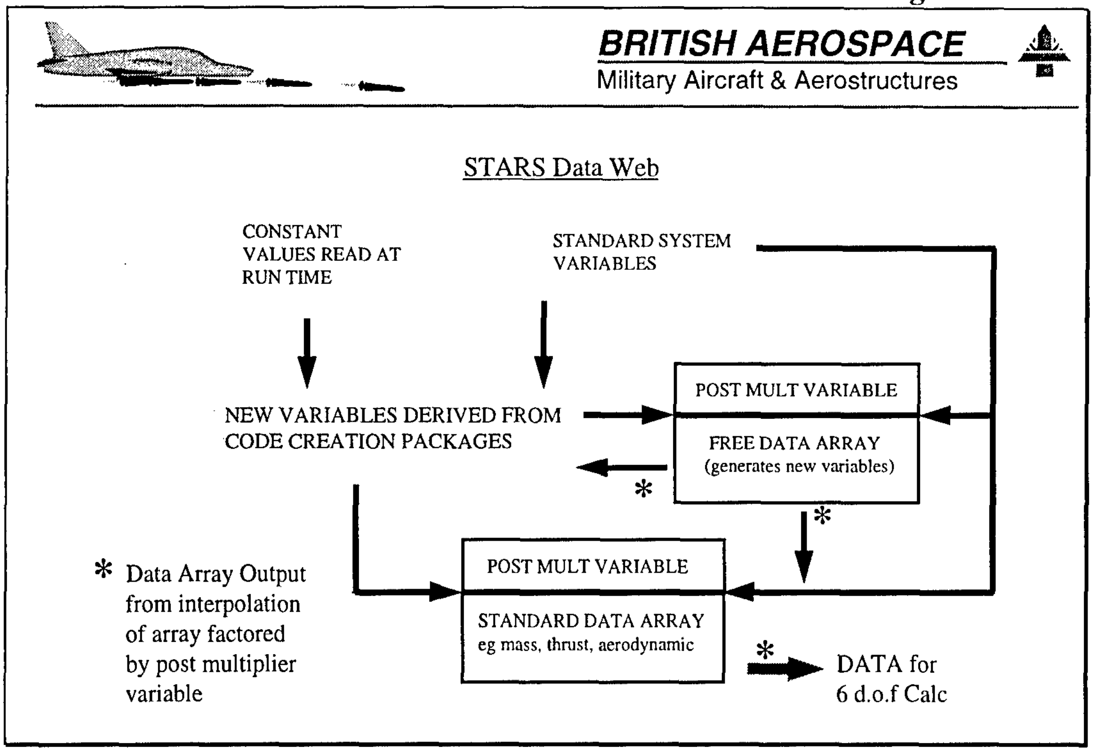

Figure 4

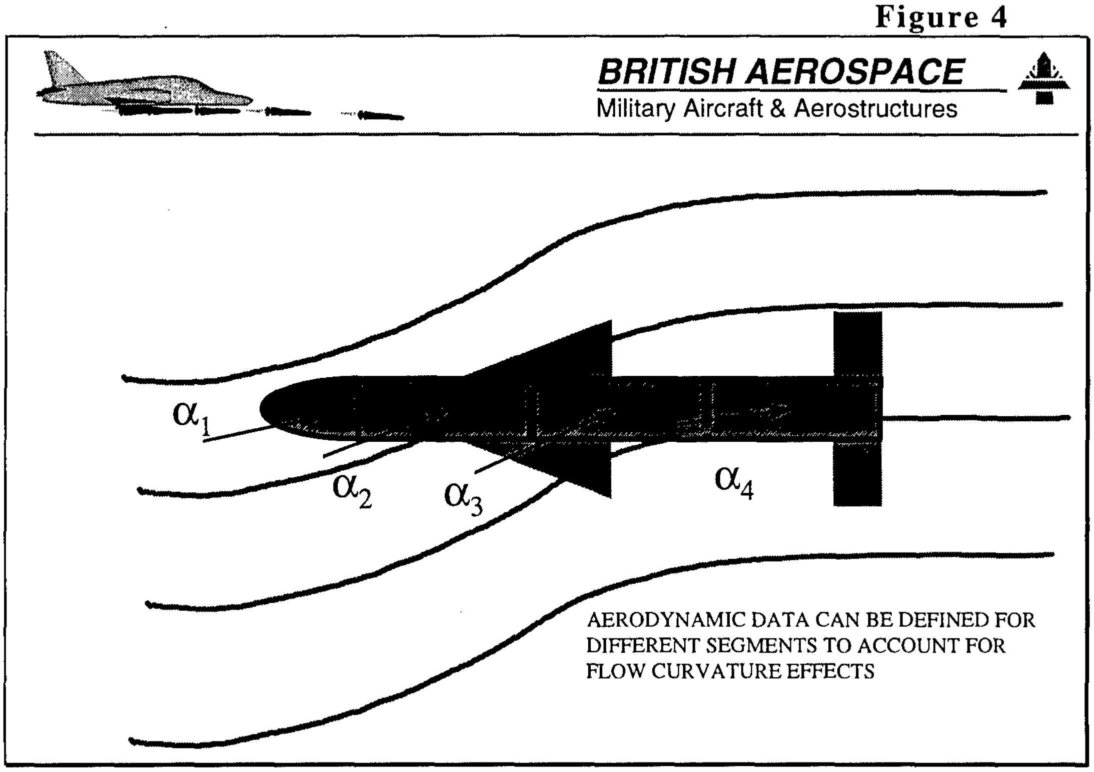

Figure 5

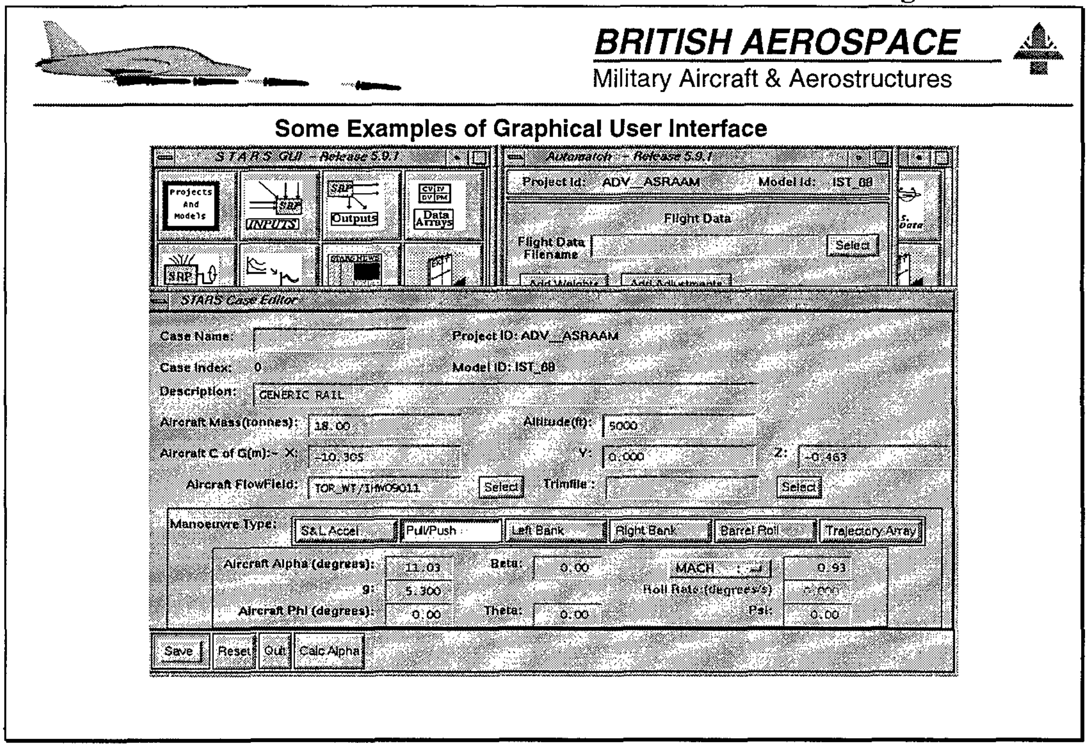

Figure 6

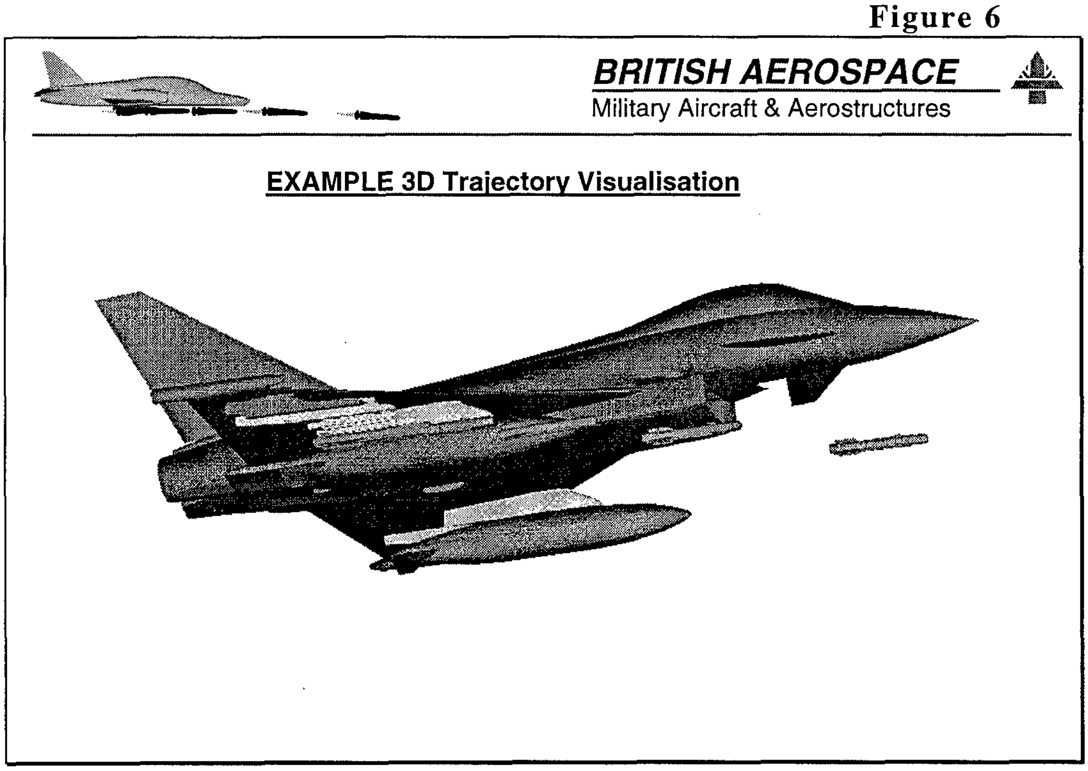

Figure 7

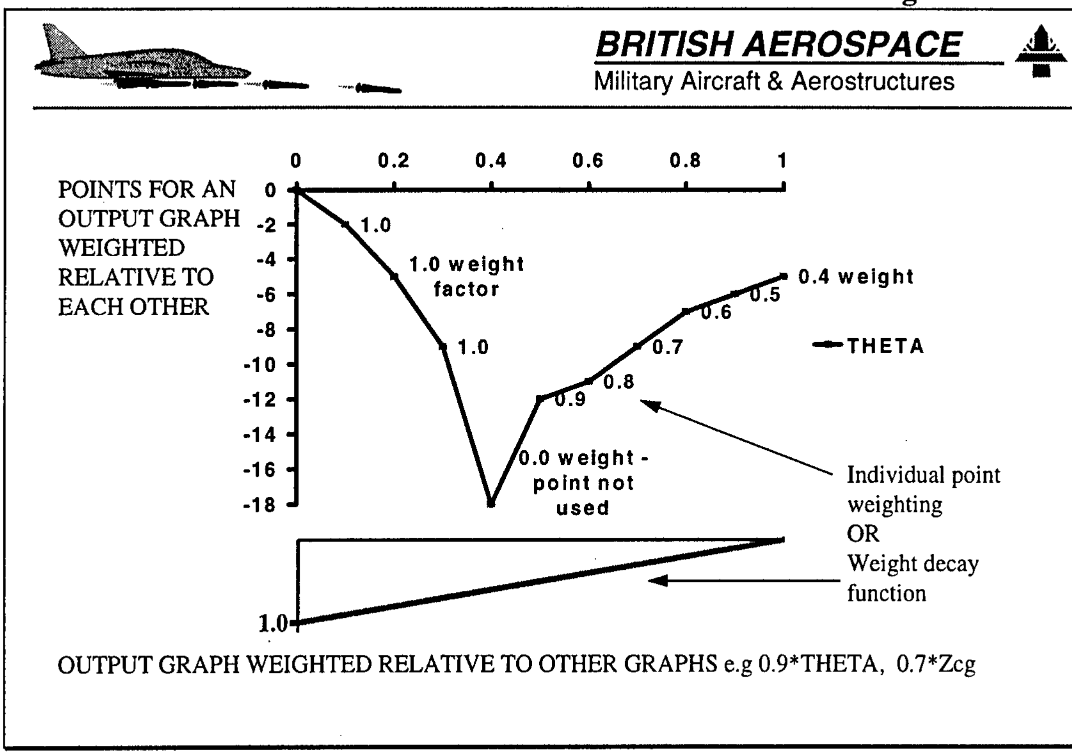

Figure 8

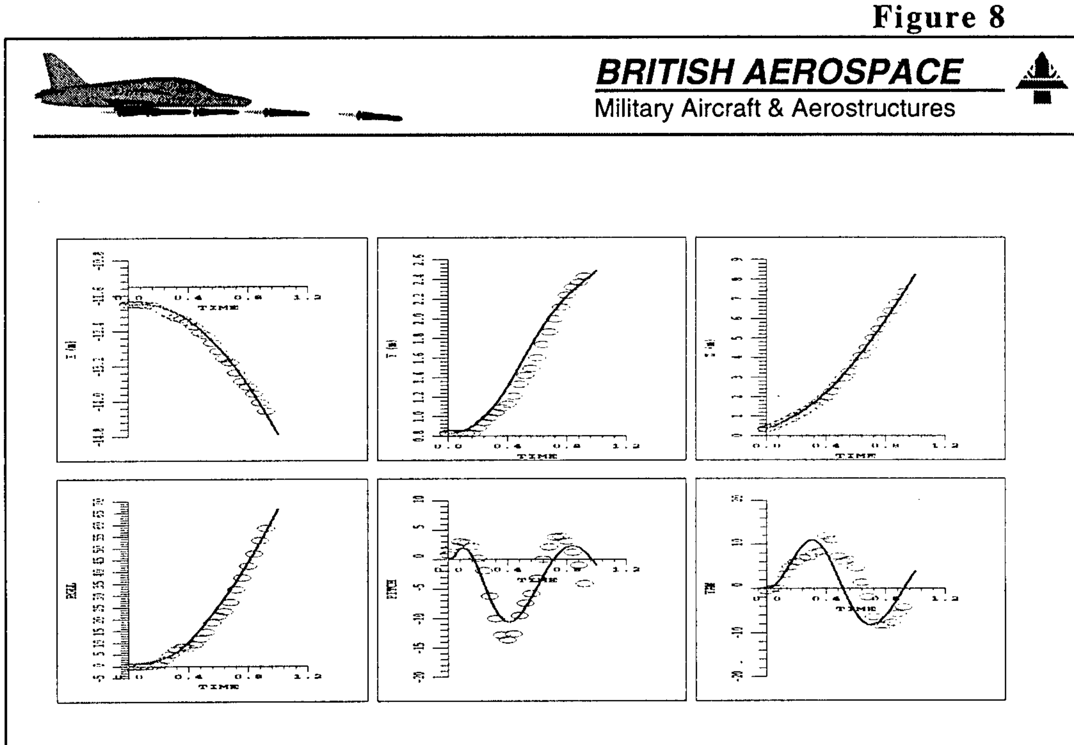

Figure 9

BRITISH AEROSPACE
Military Aircraft & Aerostructures

EXAMPLE BATCH CONTROL FILE

Aircraft trim datafile → **GR4.trm $SRPHOME/Flowfields/TOR_WT/A** ← Path and start chars of flowfield files

GRID loads.csh ← Post case shell script

Variable names and values

ACALFA 0 3 6 9 12 15
HGDST1 0.001 1.0 2.0 3.0
MCAS 0.6 0.8 0.92

EXAMPLE BATCH STATUS OUTPUT FILE

RUN 2713 CASE: AMT07004 MCAS 250;ACHGT 20000;ACNG 0.5;TFAC 1;
RUN 2714 CASE: AMT07001 MCAS 325;ACHGT 20000;ACNG 0.5;TFAC 1;
RUN 2715 CASE: AHU09001 MCAS 433;ACHGT 20000;ACNG 0.5;TFAC 1;
RUN 2716 CASE: AHS07008 MCAS 250;ACHGT 20000;ACNG 1;TFAC 1;

Cases added as runs completed

Figure 10

BRITISH AEROSPACE
Military Aircraft & Aerostructures

EXAMPLE SCATTER ANALYSIS

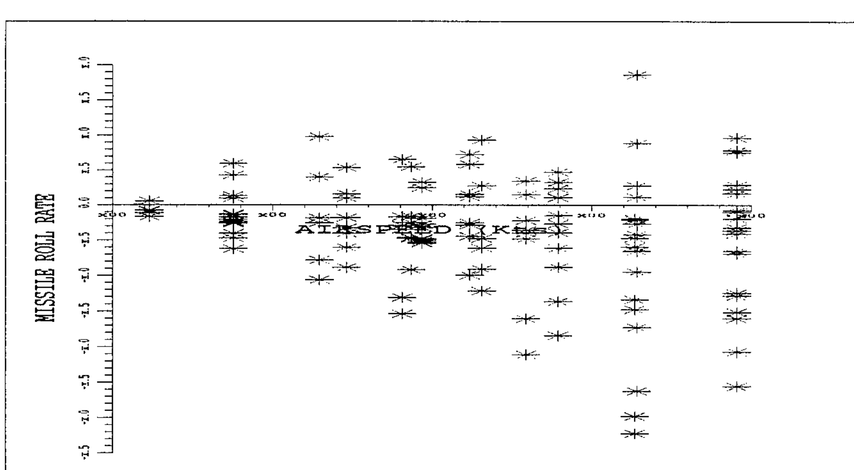

Figure 11

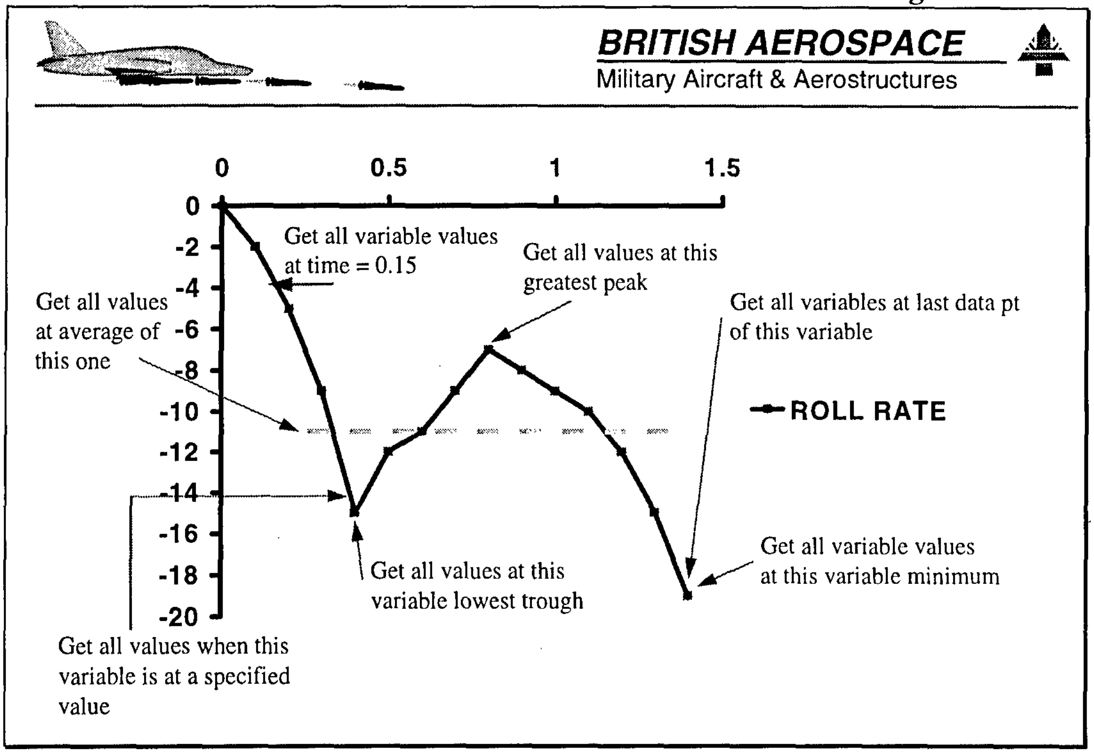

Figure 12

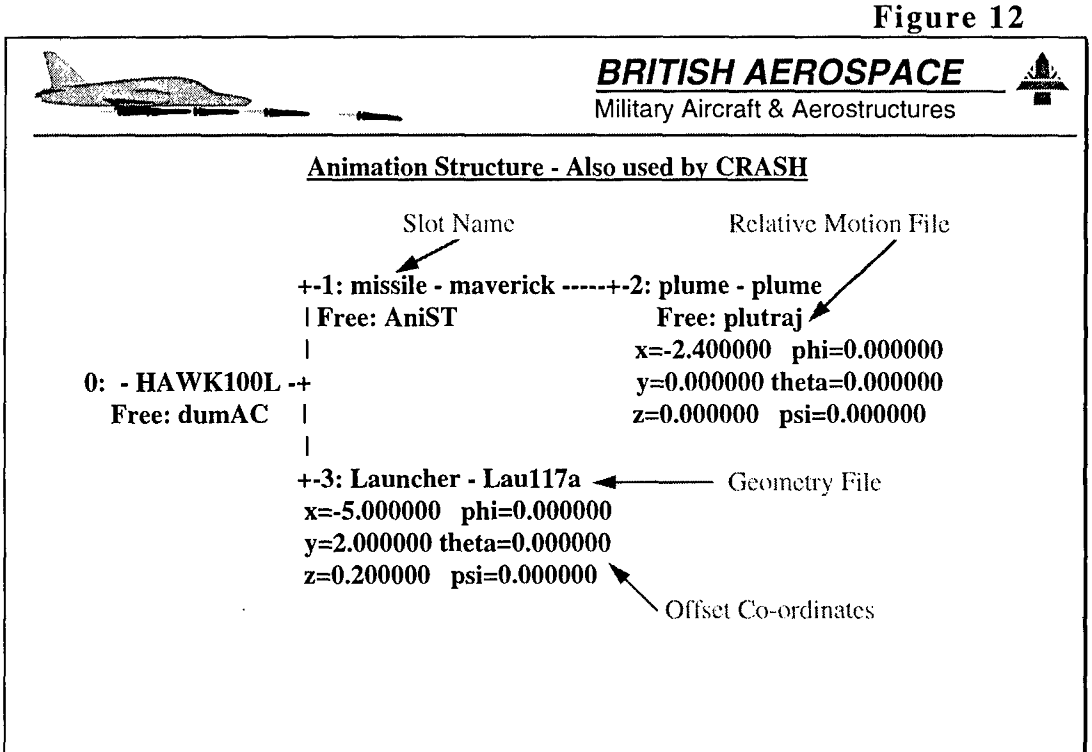

Figure 13

BRITISH AEROSPACE
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EXAMPLE CRASH OUTPUT (only one timepoint shown)

Time Pt 29 (0.330000 secs)

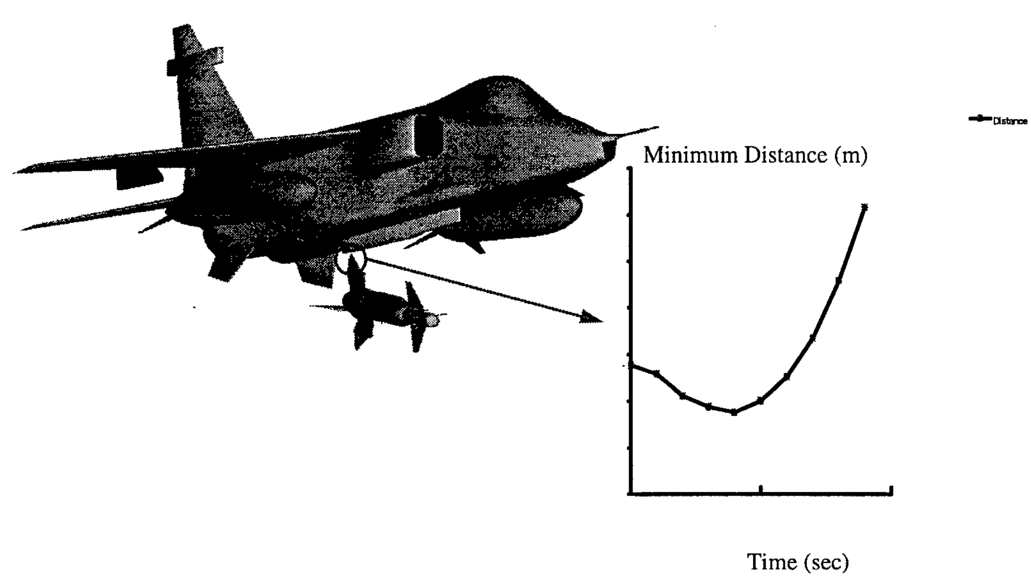
Geometry	0	4	5	6	7
0 - JAGUAR	--------	0.6154	1.2692	1.3880	0.8421
4 Fins1 - GBU24UKW	0.6154	--------	--------	--------	--------
5 FINS2 - GBU24UKW	1.2692	--------	--------	--------	--------
6 FINS3 - GBU24UKW	1.3880	--------	--------	--------	--------
7 FINS4 - GBU24UKW	0.8421	--------	--------	--------	--------

Minimum distance
GBU24 - GBU24UKZ Fins1 - GBU24UKW -- - JAGUAR 0.615360

SUMMARY
=======
Time range 0.150000 - 0.330000
Geometries 0 4 5 6 7
Minimum distance of 0.175941m at t=0.230000s between geometries - JAGUAR & Fins1 - GBU24UKW (0 & 4)

Figure 14

BRITISH AEROSPACE
Military Aircraft & Aerostructures



F/A-18C STORE CARRIAGE LOADS PREDICTION AND MUTUAL INTERFERENCE AERODYNAMICS

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Patuxent River MD 20670-1906 USA

1. SUMMARY

A computational aerodynamics study of the integration of a variant of the Joint Direct Attack Munition (JDAM) store onto the F/A-18C aircraft was performed. Computational forces and moments, derived from hybrid Euler/Navier-Stokes solutions, correlated fairly well with available wind tunnel test data across a wide angle-of-attack range at both transonic and supersonic freestream flow conditions. The computational results were analyzed to explore the aerodynamic influence of the store on an adjacent fuel tank, and the aircraft wing and fuselage. The addition of the JDAM caused a 16% reduction in the outboard yawing moment of the 330 gallon tank. The presence of the store had nearly no effect on the forward 30% of wing; however, there were significant effects on both the upper and lower surfaces of the wing aft of mid- chord. The influence of the store was so pervasive that it was detectable as far forward as the canopy and as far aft as the empennage.

2. LIST OF SYMBOLS

c .... Store reference length (14.5 inches)
cg .... Center of gravity
Cp* ...... Critical pressure coefficient
CN .... (N/qS) Normal force coefficient (positive up)
CY .... (Y/qS) Side force coefficient (positive outboard)
CA .... (A/qS) Axial force coefficient (positive aft)
Cm ...... (m/qSc) Pitching moment coefficient (positive nose up)
Cn .... (n/qSc) Yawing moment coefficient (positive nose-outboard)
S .... Store reference area (165.12 square inches)
Xcg ..... Store x cg coordinate (452.737)
Ycg ...... Store y cg coordinate (134.28)
Zcg ...... Store z cg coordinate (68.371)
α .... Aircraft angle-of-attack (degrees)

Store forces and moments are resolved into the store body axes. All moments are resolved about the store's center of gravity.

3. INTRODUCTION

During any stores integration program, the aerodynamic loads of stores in captive carriage play a significant role in determining the structural adequacy of the store and parent airframe and the separation characteristics of the store. In addition, due to the non-linearity of aerodynamic flows at transonic speeds, the integration of external stores may strengthen existing and generate new shock waves as well as flow separation patterns, both of which can have a significant impact on the performance and handling qualities of the aircraft. In light of this observation, it is unsettling that aircraft are still designed without consideration of the influence of stores in the initial design space. Alternatively, this situation begs for us to take advantage of an obvious opportunity to make significant improvements in the aerodynamic performance of the complete weapon system. After all, a strike/fighter aircraft without weapons is an expensive target.

This paper explores aerodynamic results, in terms of integrated forces and moments as well as the mutual interference flowfield, of a Computational Fluid Dynamics (CFD) study of a version of the BLU-109 Joint Direct Attack Munition (JDAM). The JDAM was held in captive carriage on the outboard wing station #2 in the presence of an adjacent 330 gallon tank on station #3 on the F/A-18C aircraft. The computations were actually conducted to support a Navy flight clearance of a variant of the JDAM during the competitive phase of the weapon's development program. One of two JDAM prototypes built for the program returned from a captive carriage flight on an F-16 test aircraft with structural damage to the store's fins. To ensure an uneventful flight of the only remaining JDAM prototype on the F/A-18C, CFD predicted aerodynamic distributed loads were used, along with a finite element structural analysis, to assess the structural adequacy of the store in carriage on the F/A-18C at various flight conditions. A CFD model of the JDAM was generated and integrated with an existing CFD model of the F/A-18C. The first CFD solution was available in eight days from the time the JDAM geometry was received. The entire aerodynamic and structural analyses were completed in a period of

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

three weeks, in time to clear a successful flight test. The time estimated to conduct a conventional wind tunnel test instead of the CFD analysis to obtain distributed aerodynamic loads was nine months, which would have significantly delayed and/or added undue risk to the weapon's development program.

4. GEOMETRY AND GRID GENERATION

The F/A-18C geometry and grids for this analysis had been developed in a previous analysis.[1] The engine inlet and boundary layer divertor were faired over and an aft-mounted sting was included in the geometry. The horizontal and vertical tails were not present in the computations. The F/A-18C geometry was represented by 7 overlapping inviscid grids totaling 924,443 points, including the forebody/cockpit, the leading edge extension (LEX), center fuselage, afterbody, wing (including the wingtip missile launcher), and a wing/fuselage collar grid as shown in Figure 1.

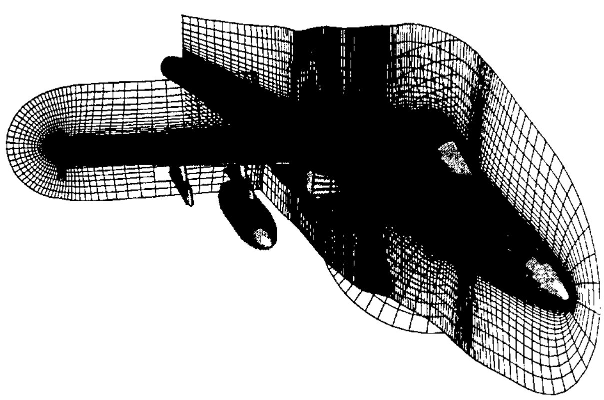

Fig. 1. Composite overset grid of the F/A-18C aircraft with wing pylons and a 330 gallon tank on wing station #3.

The wing leading and trailing edge flaps and ailerons were set at zero deflection. The area in between the exhaust nozzles was also distorted and projected to the downstream computational boundary. The forebody/cockpit, center fuselage and afterbody grids extended to the farfield which was seven mean aerodynamic chord lengths away from the body in all directions.

The pylon geometry was developed from line drawings and physical measurements. The upper surfaces of the pylon grids conformed to the wing lower surface and the grid consisted of 116,679 points as shown in Figure 2.

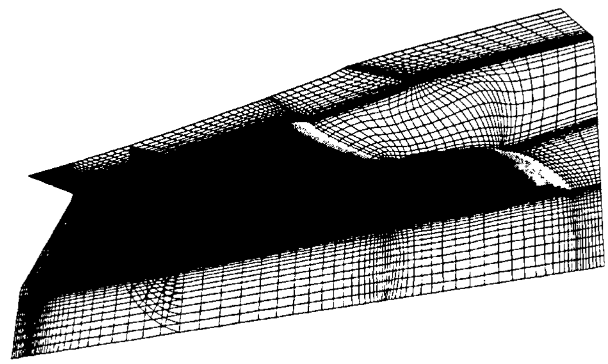

Fig. 2. Wing pylon geometry and field grid.

The 330 gallon fuel tank geometry was obtained from line drawings which specified an analytically defined shape. The tank grid consisted of 44,895 points as shown in Figure 3.

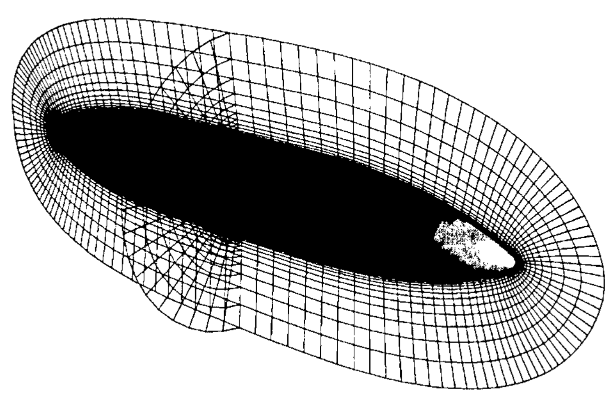

Fig. 3. Geometry and field grid of the 330 gallon tank.

The Aircraft/Stores Interface Manual was used to position the pylons and the tank relative to the F/A-18C wing.[2]

The JDAM store geometry is that of a previous configuration that is no longer flying on the aircraft. The geometry was obtained from IGES files and line drawings. The geometry of the upper surface hardback was faired into the body of the bomb. Sway braces, lugs, cavities and interface connections were not modeled. Viscous grids were generated by clustering at least 21 points within the boundary layers with a $y^+ = 10$ of the first point off the wall as a goal. The grid consisted of 15 overlapping zones and 995,530 points as shown in Figure 4.

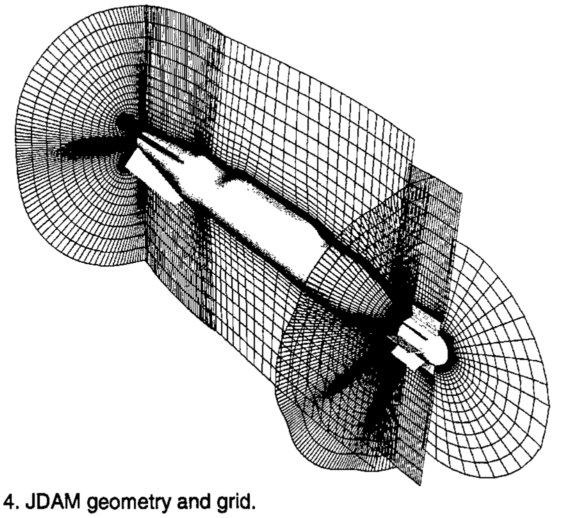

Fig. 4. JDAM geometry and grid.

To ensure good connectivity of the grids, a dense Cartesian type grid, consisting of 234,465 points, was added below the aircraft wing, blanketing the pylons and stores. The upper boundary of the grid conformed to the wing lower surface. The entire grid, representing the complete right side of the aircraft, including pylons and stores, was 3,013,787 points.

5. COMPUTATIONAL METHOD

The OVERFLOW code was used to solve the Euler/Navier-Stokes cases presented. The OVERFLOW code is a finite difference, Chimera flow solver capable of solving the Thin-Layer Reynolds Averaged Navier-Stokes equations in overlapping grids.[3] The numerical scheme used was the block tri-diagonal, approximately factored algorithm with second-order accurate central differencing of the inviscid and viscous terms. Default levels of scalar second- and fourth-order artificial dissipation were used to stabilize the numerical algorithm. The Baldwin-Lomax algebraic turbulence model was used in the viscous zones for the computations presented.

The Domain Connectivity Function Three-Dimensions (DCF3D) code was used to cut holes in the overlapping grids and construct the inter-grid connectivity stencils.[4] This version of DCF3D used prescribed analytical shapes, such as ellipsoids and cylinders, to cut holes in the overlapping grids.

6. RESULTS

The flow conditions presented in this paper are at Mach 0.95 and 1.2 at aircraft angles-of-attack between -4° and 12° degrees, zero sideslip, and at a Reynolds number of 2.8 million based on the mean aerodynamic chord of the F/A-18C (C_{mac} = 138.28 inches).

An analysis of the mutual interference aerodynamics focuses on the solutions with and without the presence of the JDAM at carriage for the Mach 0.95, $\alpha = 4^\circ$ case, exclusively. The surface pressure coefficient of the 330 gallon tank and JDAM at captive carriage at these flow conditions is rendered below in Figure 5. Note that although the tails are present in the figure, they were not included in any of the computations. It is interesting to note also that vortices from the leading edge extension exist at this relatively low angle-of-attack flight condition.

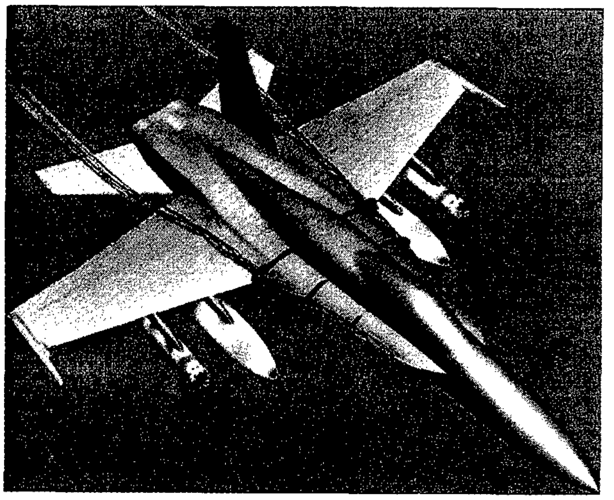

Fig. 5. Representative solution of the JDAM in carriage. Surface pressure coefficient for Mach 0.95, $\alpha = 4^\circ$ is rendered on the 330 gallon tank and JDAM. The LEX vortex is visualized with particle traces as well as contours of vorticity at three spanwise cuts above the LEX.

6.1 Correlation with Experimental Data

Experimental forces and moments of the JDAM were available from previous wind tunnel testing in which the loads were measured by a pylon mounted balance.[5] The normal and side forces were within a few percent of the test data across the Mach number, angle-of-attack range analyzed. The correlation between the CFD predictions and the experimental data improved with the addition of the Cartesian grid placed under the wing, blanketing the pylons and stores. This grid provided better resolution of the flow physics as well as good connectivity among the overlapping zones. Axial forces, however, were still under-predicted compared to test data. A correlation of the pitching and yawing moments, which are the significant drivers in store separation, is shown in Figures 6a and 6b.

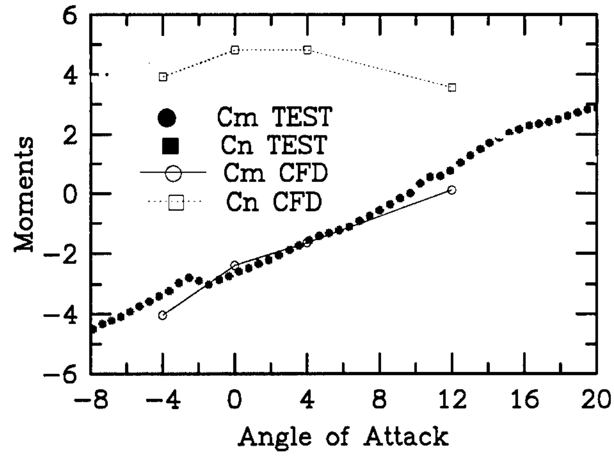

Fig. 6a. Predicted and experimentally measured captive carriage pitching and yawing moments of the JDAM at Mach 0.95.

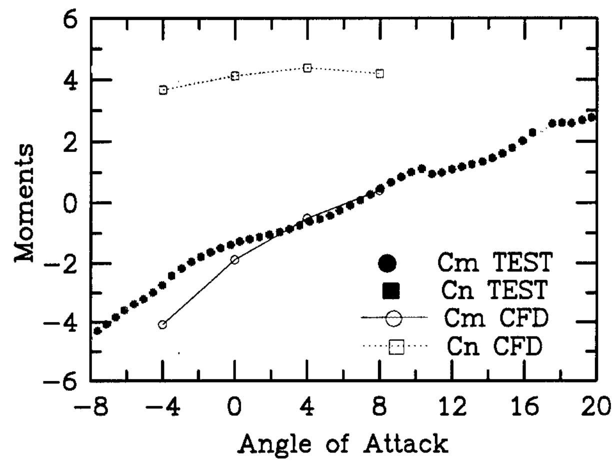

Fig. 6b. Predicted and experimentally measured captive carriage pitching and yawing moments of the JDAM at Mach 1.2.

The moments are fairly well predicted by the computational approach and could be used as the initial condition of a separation analysis, using a six degree-of-freedom dynamic model. However, a notable degradation in the correlation of the pitching moment exists at an angle-of-attack of -4 degrees for the supersonic case. At negative angles-of-attack, the lower wing surface becomes the suction side, generating more complicated flow features that are more difficult to predict accurately. It is believed that the level of fidelity of the computations would improve if additional grid points and viscous boundary layers on the wing lower surface, pylons and adjacent tank were added.

6.2 Mutual Interference Aerodynamics

Shown below in Figure 7 is a qualitative comparison of the character of the mutual interference aerodynamic flowfield at Mach 0.95, $\alpha = 4^{\circ}$. The figure shows a planform view from below the aircraft of the pressure coefficient on a horizontal cutting plane at an aircraft waterline of z = 67 inches (approximate centerline of the 330 gallon tank).

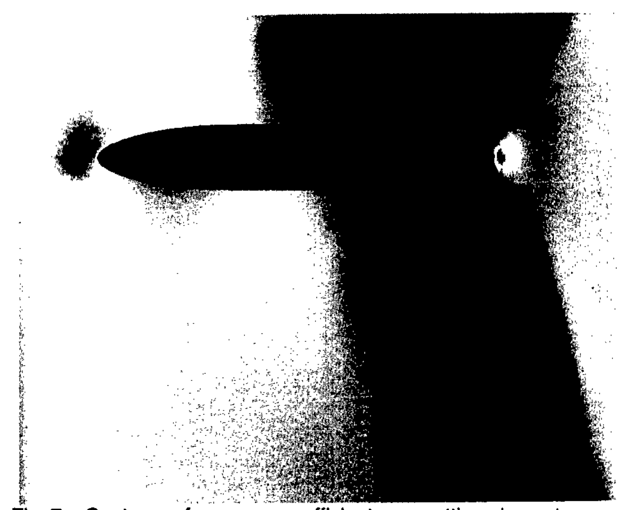

Fig. 7a. Contours of pressure coefficient on a cutting plane at a waterline of 67 inches for the aircraft without the JDAM in captive carriage at Mach 0.95, $\alpha = 4^{\circ}$. (Fuselage is up).

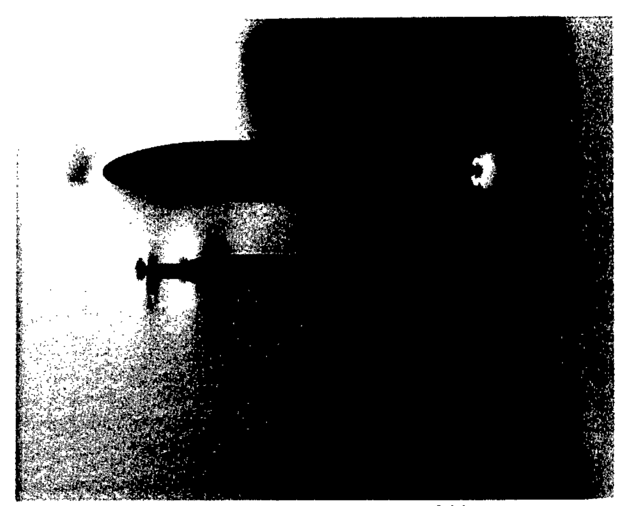

Fig. 7b. Contours of pressure coefficient on a cutting plane at a waterline of 67 inches for the aircraft with the store in captive carriage at Mach 0.95, $\alpha = 4^{\circ}$. (Fuselage is up)

With the store in carriage, the recovery shock between the tank afterbody and fuselage, moves upstream on the fuselage. In addition, a strong expansion is evident between the 330 gallon tank and the JDAM at the leading edges of the aft fins of the JDAM. The wake of

the JDAM is shown as it disturbs the recovery shock wave emanating from the afterbody of the 330 gallon tank. Also, local expansions and shock waves are generated by the forward portion of the JDAM, which influence the surface pressure on the forward portion of the tank.

6.2.1 Effect on External Tank

The impact on the integrated forces and moments of the 330 gallon tank at Mach 0.95, $\alpha = 4°$, caused by the addition of the JDAM is tabulated in Table 1.

	Empty Pylon	Store in Carriage	% Difference
CN	0.812	0.799	-1.6
CY	-0.114	-0.113	1.1
CA	0.700	0.732	3.3
Cm	-0.523	-0.513	1.9
Cn	0.767	0.646	-15.8

Table 1. Influence of JDAM on 330 gallon tank integrated forces & moments at Mach 0.95, $\alpha = 4°$. Tank reference length=28.8 inches, tank reference area = 652.1 sq. inches, tank cg (x=446.9, y=88.0, z=65.2)

The increment in normal, side, and axial forces and pitching moment is less than 5%. As expected, axial force increases. However, the presence of the JDAM results in a 16% reduction in outboard yawing moment of the tank.

The surface pressure coefficient along lines extending from the nose to the afterbody on the inboard and outboard surfaces of the tank is shown in Figure 8. The surface pressure coefficients for both cases, with and without the presence of the adjacent JDAM, clearly show a nose outboard yawing tendency. The effect of adding the JDAM is to nearly evenly increase the pressure on the entire inboard surface of the tank. On the outboard tank surface, the pressure on the forward portion and the suction on the aft portion increase, thereby exerting the 15.8% nose inboard yawing moment increment. Thus, the yawing moment increment is attributed to the change in distributed pressure on the outboard surface of the tank only. Surprisingly, the surface pressure over the center portion of the tank is hardly affected. The flow separates over the last several percent of the tank, as shown in the figure, in spite of the fact that the tank flowfield was resolved with the Euler equations!

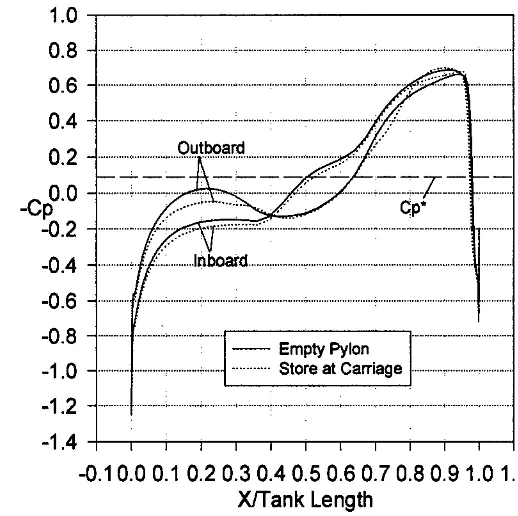

Fig. 8. Cp distribution on inboard and outboard sides of the 330 gallon fuel tank with and without the JDAM store in captive carriage at Mach 0.95, $\alpha = 4°$.

6.2.2 Effect on Aircraft Wing

The surface pressures on the lower wing surface, at Mach 0.95, $\alpha = 4°$, with and without the presence of the JDAM in carriage, are shown in Figures 9a and 9b.

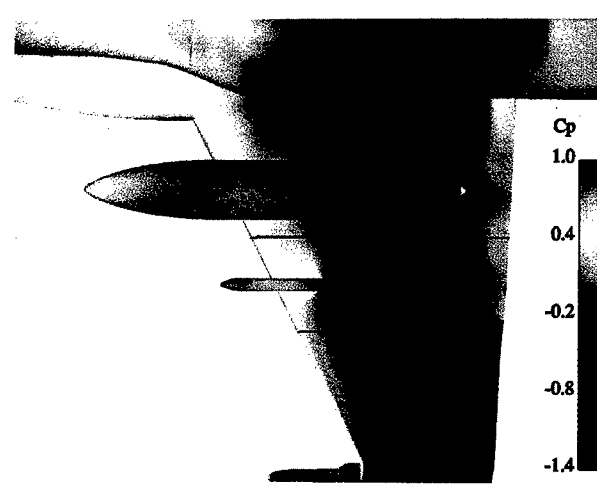

Fig. 9a. Contours of surface pressure coefficient on the wing lower surface without the JDAM store in captive carriage at Mach 0.95, $\alpha = 4°$.

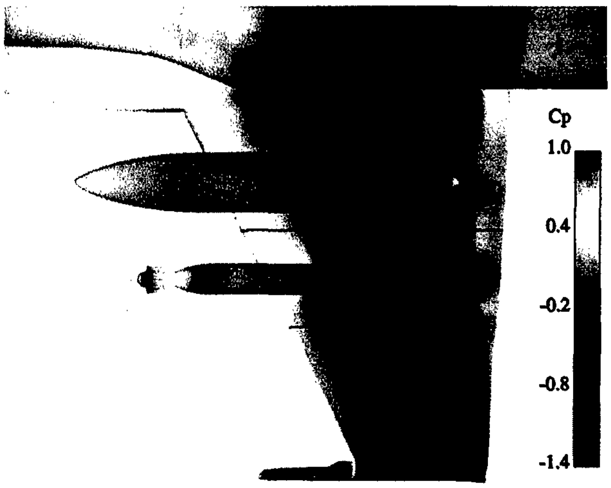

Fig. 9b. Contours of surface pressure coefficient on the wing lower surface with the JDAM store in captive carriage at Mach 0.95, $\alpha = 4^{\circ}$.

The black streamwise lines in Figures 9a and 9b indicate constant buttlines of 111.14 and 157.42 inches span along which the surface pressure coefficient was plotted in Figures 10a and 10b.

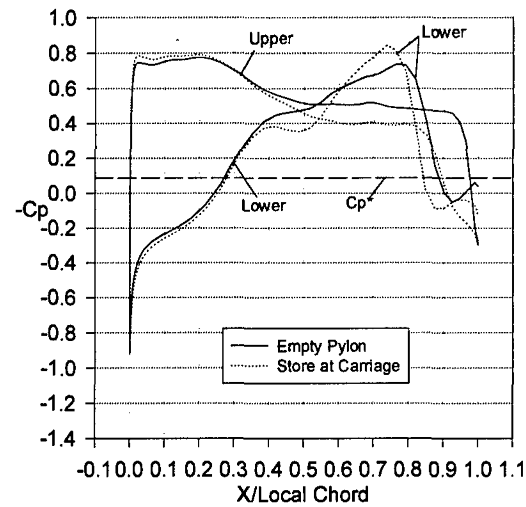

Fig. 10a. Buttline 111.14 surface pressure coefficient distribution with and without the JDAM store in captive carriage at Mach 0.95, $\alpha = 4^{\circ}$.

The presence of the JDAM in carriage has little affect on the forward 30% of the aircraft wing. Significant effects on the wing, however, occur as a result of shock interaction between the store and wing on the aft portion of the wing.

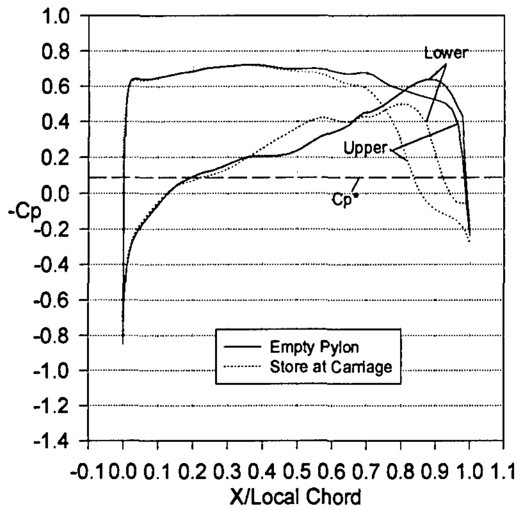

Fig. 10b. Buttline 157.42 surface pressure coefficient distribution with and without the JDAM store in captive carriage at Mach 0.95, $\alpha = 4^{\circ}$.

A buttline of 111.14 inches is halfway between the wing pylon stations. At this buttline, the forward portion of the wing carries a slightly higher lift coefficient as a result of increased upper surface suction and lower surface compression. This would cause a higher hinge moment on the leading edge flap. The wing lower surface experiences reduced suction at 50% chord, followed by increased suction at 70% chord, and is also followed by a stronger and more upstream recovery shock. Surprisingly, the presence of the store has dramatic effect on the upper wing surface. The wing upper surface experiences a significant loss in suction across the aft 50% chord and a weaker, more upstream recovery shock.

At a buttline of 157.42 inches, the wing lower surface experiences an increase in suction at 50% chord and a weaker, more upstream recovery shock. The upper surface experiences a significant lift loss as a result of an upstream shift equivalent to 20% chord of the recovery shock. This upstream shift of the shock could cause boundary layer separation over the trailing edge of the wing and a significant loss of flap effectiveness.

One must keep in mind that since the Euler equations were used to resolve the wing aerodynamics in this study, viscous effects have been ignored. At transonic speeds, viscous effects can dominate, making the influence of the JDAM even more pervasive and potentially more damaging to the aerodynamic performance of the aircraft.

6.2.3 Effect on Aircraft Fuselage

The surface pressure coefficient along the aircraft centerline, at Mach 0.95, $\alpha = 4^{o}$, with and without the JDAM is plotted in Figure 11.

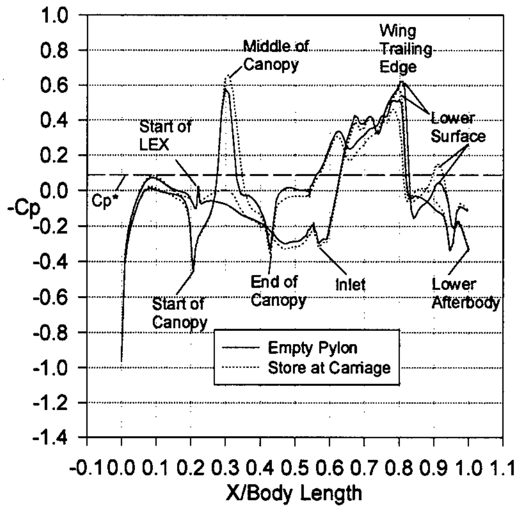

Fig. 11. Centerline upper and lower fuselage surface pressure coefficient distribution with and without the JDAM store in captive carriage at Mach 0.95, $\alpha = 4^{o}$.

The forward 20% of the aircraft remains essentially unaffected by the addition of the JDAM on the wing station. However, over the canopy, the flow expands more and the recovery shock strengthens as a result of the presence of the store. On the upper surface of the fuselage, the aircraft experiences a mild loss in suction between 45-80% of the fuselage length and a reduction in compression over the empennage. The loss of suction over the fuselage is consistent with the loss of suction over the aft 50% of the wing upper surface. The afterbody recovery over the last 5% of the aircraft length, however, remains nearly constant.

Along the lower fuselage surface, there is a marked reduction in compression along the area below the cockpit and only a mild compression between 35-80% of the fuselage length. The recovery on the lower surface behind the wing is less pronounced and a suction peak develops at 90% of the fuselage length. It is remarkable how pervasive the effect of adding the JDAM onto the wing pylon is on aerodynamics of the fuselage.

7. CONCLUSIONS

This paper describes the successful and timely use of CFD in the aircraft store's integration process. Forces and moments, derived from hybrid Euler/Navier-Stokes solutions, of the JDAM store in carriage on the F/A-18C wing, correlated fairly well with available wind tunnel test data across a wide angle-of-attack range at both transonic and supersonic freestream flow conditions. To produce accurate predictions, the computational grid resolution and the overlapping grid connectivity under the wing near the store was improved. Based on these computations, the aerodynamic influence of the aircraft was more significant than expected. The addition of the JDAM caused a 16% reduction in the nose outboard yawing moment of the 330 gallon tank. The presence of the store had nearly no effect on the forward 30% of the wing; however, there were significant effects on both the upper and lower surfaces of the wing aft of mid-chord. A shock on the outboard wing upper surface was shifted 20% upstream. This could cause boundary layer separation and undesirable effects on the trailing edge flap and aileron effectiveness. The influence of the store was so pervasive that it was detectable as far forward as the canopy and as far aft as the empennage. Based on this study, the aerodynamic influence of external stores on aircraft should be incorporated early in the design process to mitigate undesirable flow characteristics and potentially improve the aerodynamic performance and handling qualities of the complete weapon system.

8. REFERENCES

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A Method Of Predicting Weapon Ballistics Prior To Flight Trials Using Existing 6 DoF Modelling Techniques

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1. SUMMARY

The process of design and clearance of a modern military aircraft can span decades with the evolution of the design, build, testing and clearance phase leading to the final product. With the drive to shorten these timescales and reduce costs in order to supply the customer with an aircraft as early as possible, any reduction in this cycle time is advantageous.

Although the tasks of ballistic modelling and safe separation share a fundamental methodology, in that they both deal with the trajectory of a weapon after it has separated from its parent aircraft, they have until recently been treated as two totally separate tasks.

This paper outlines the benefits which can be accrued by using the safe separation models to provide trajectory data ahead of any flight trials. This includes benefits from reductions in both the ground based modelling and flight trials areas, and outlines how this work can improve the accuracy of ballistic data supplied prior to any flight trials work and improve ground impact patterns.

2. List Of Symbols/Abbreviations

DoF	Degree Of Freedom
GFI	Government Furnished Information
GFF	Government Furnished Facilities
MRI	Minimum Release Interval
STARS	Stores Trajectory And Release Simulation
α_t	True angle of attack
δ	Flap deflection
ε	Leading edge (slat) deflection
ϕ	Roll attitude
η	Foreplane deflection

3. Introduction

In the UK weapon aiming data has traditionally been supplied to the airframe manufacturer, for incorporation into the 'attack computer', as GFI. In general this data has been statistically derived based on extensive use of flight trials and the expenditure of large numbers of stores, in some notable cases several hundred bombs have been dropped to evaluate a single store/aircraft combination, at considerable expense. These trials are carried out in addition to the flight trials used to validate the safe separation modelling.

Mathematical modelling techniques used for these two tasks are similar in concept i.e. they deal with essentially the same problem of store motion after release from the aircraft, with only the duration of interest and the level of fidelity to the precise motion of the store varying between the two. It would seem therefore that co-operation between these areas could yield substantial benefits by using the high definition model to pre-empt the flight trials.

This paper outlines the work carried out at BAe MA&A within this overlap of tasks, and details the expected benefits to be gained for future aircraft in terms of time and costs.

4. Background

The first example of this overlap occurred at BAe MA&A in 1992 when additional trajectory data was generated for use in calculation of the MRI for TORNADO in the 8 bomb configuration with UK 1000lb retarded bombs. This data was used to improve the aircraft self damage assessment for service release recommendations on export aircraft.

As a result of this when initial weapon aiming data was made available for EF2000 based on 'best estimate' from previous aircraft, an

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

assessment of the expected miss distances was requested by the Attack And Ident system group. This showed that based on the data available at that time significant errors (100s of feet) could be expected for the UK 1000lb bomb in free fall mode.

This initial assessment was considered "crude" as the model used did not utilise all of the data available, hence a follow on assessment was conducted to incorporated all of the available information.

5. Assessment Methodology

The entire assessment methodology relies on mathematical modelling using both 2 and 6 degree of freedom calculations. At BAe both types of model are created within the corporate package STARS. This has the advantage that both input and output can be kept as near identical as possible easing comparison tasks. The two model types are outlined below.

5.1 Point Mass 2 DoF

These models are re-creations of the weapon aiming algorithms used on the aircraft and as such they are relatively simple models (**fig 1**), composed of:-

1. Single mass values
2. Ejection velocity as a function of aircraft flight speed
3. Drag area as a function of either one or two variables (MACH Number and time are normal)

Thus the models generate only motion in the X and Z planes. Within the STARS environment this has been extended to allow cross wind, strength and direction as a function of height, to be applied, to allow accurate matching of flight trials data.

5.2 Separation Model 6 DoF

The 6 Degree Of Freedom model is normally used for safe separation studies and as such must provide an accurate representation of the motion of the store in all 6 axes. It requires considerably more detail than the point mass model (**fig 2**). In order to fulfil this requirement the model would normally include the following components:-

1) Free air baseline aerodynamics split into at least nose (Cy and Cz) tail (Cy and Cz) and body (Cx and Cl).
2) Installed loads usually derived from wind tunnel testing and decayed using established laws.
3) Free air damping derivatives.
4) Mass, centre of gravity and inertia values.
5) Store flight control system if fitted.
6) Release system performance (ERU, rail etc).

Within STARS all of the above can be a function of almost any variable. Free air data is normally a function of MACH Number, α_t and ϕ and in some cases, time, configuration and control surface deflection (δ,ε and η). Installed loads are usually a function of aircraft store configuration and aircraft control/lift surface deflection.

During the development flight trials these models are matched to the store behaviour within the near field of the aircraft (**fig 3**), using data derived from aircraft mounted cameras. As this matching is confined to close proximity of the aircraft and relatively short timescales, in the order of 1$\rightarrow$2s at most, it is influenced most strongly by the ejector performance and installed loads.

The longer term motion (**fig 4**) is governed by the free air aerodynamics and thus the two portions of the motion are reasonably independent.

6. Overall Methodology

Based on this information the following methodology was determined for conversion of one weapon from aircraft to aircraft (**fig 5**).

1. Obtain the weapon aiming model for the current aircraft and determine its accuracy. This data is best obtained from the current operator / customer.
2. Obtain the safe separation model for the same aircraft/weapon combination. This

should be matched to the near field motion from flight trials.

3. By modification of the free air data, usually drag alone, match the safe separation model run down to ground to the weapon aiming model.

4. Check that the changes made to the safe separation model have not adversely affected the near field match.

5. Transfer the matched free air to the new aircraft and use this to generate synthetic flight trials data on which the first pass weapon aiming algorithms can be based.

6. Conduct the safe separation flight trials. In order to obtain the optimum cost effectiveness these trials should be conducted over an instrumented range to allow ballistic (down to ground) data to be obtained as ride along.

7. Match the safe separation model in both near **and far** field using aircraft and kinetheodolite data respectively.

8. Use this matched model to predict/assess the weapon aiming data.

This methodology will result in a matched model suitable for predicting both safe separation and weapon aiming data. The first pass data (stage 6) can be available prior to any flight trials and can therefore be incorporated and tested in parallel to the safe separation trials well before any aircraft is delivered to the customer.

A similar approach has been investigated previously in the US (Ref:1) and shown to give a very good match to flight trials results and also how such a methodology can be used to optimise the ground impact pattern (**fig 6**) as required.

It may be possible in future to derive ballistics completely theoretically using 6 DoF models, though there are store interactions that need to be simulated accurately before this could become a reality (**fig 7**).

7. Discussion

The use of the safe separation trials to gather ballistic data will require some compromise in trials conditions to satisfy both requirements. This can however benefit both requirements as ballistic data is available earlier and additional data is available for safe separation studies. The aim is to reduce the overall number of trials and thereby reduce the cost of integration to the customer and increase the speed of response for new stores.

The shift away from dumb munitions to precision guided ordnance does not completely remove the requirement for weapon aiming and the consequent trials. However the accuracy required can be relaxed dependant on the manoeuvrability of the weapon in question (**fig 8**). This may result in the elimination of extensive flight trials solely for ballistic purposes as the trials requirements can be combined with the safe separation work without detriment to either.

8. Conclusion

The use of 6 DoF modelling to generate pre-flight trajectory information, for use in the initial weapon aiming data, should result in lower initial errors and consequently fewer flight trials. As this data can be available well before the aircraft is delivered to the customer, there is less risk that optimisation (via additional flight trials) will be required once the aircraft is in service.

In addition the combining of the safe separation and ballistic flight trials should result in a lower overall requirement. Given the number of flight trials normally used in ballistic assessments it may be possible to save a good number of flights and the weapons expended.

9. References

Ref 1 :
'A Technique for Predicting Aircraft Flow-Field Effects Upon an Unguided Bomb Ballistic Trajectory and Comparison with Flight Test Results.'

H.Paschall Massengill, Jr
Senior Engineer
Calspan Corporation/AEDC Operations
Arnold Air Force Base TN 37389 (USA)

FIGURE 1

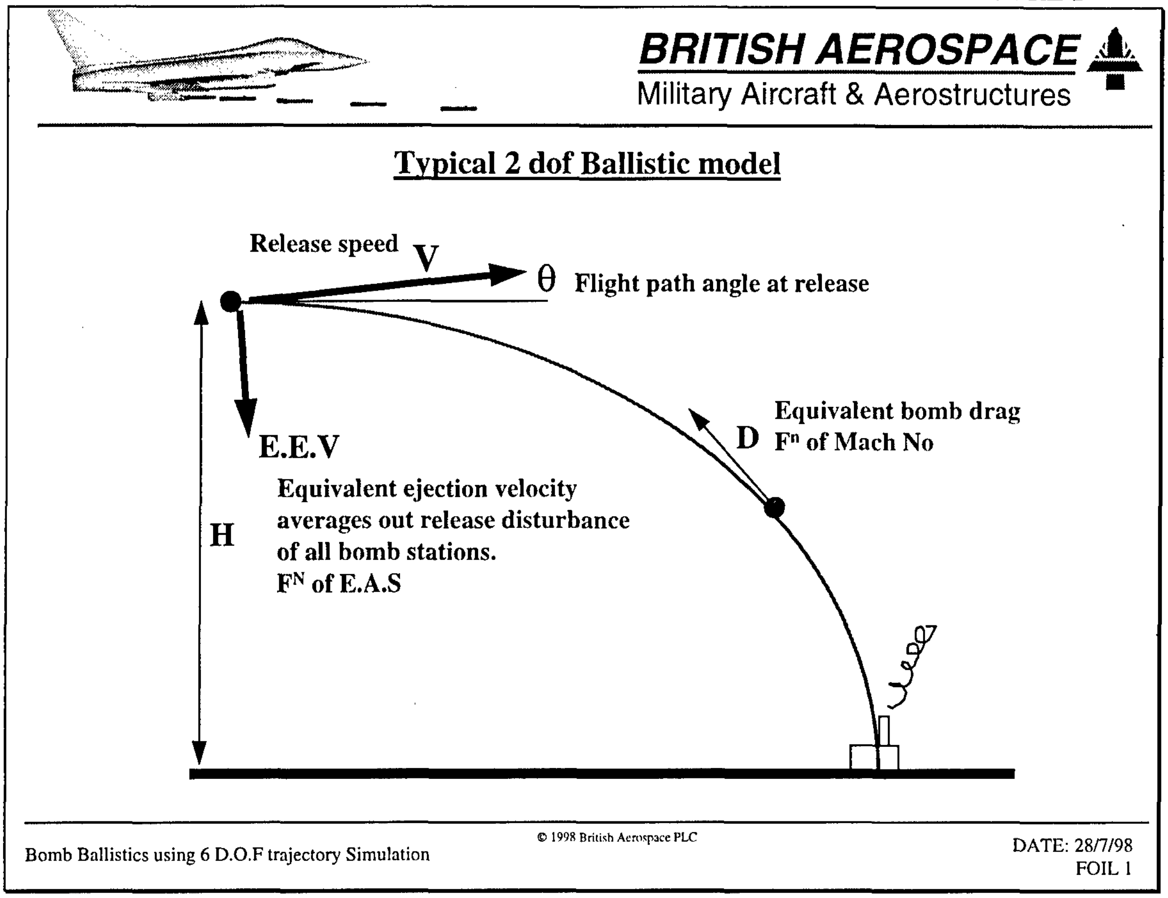


FIGURE 2

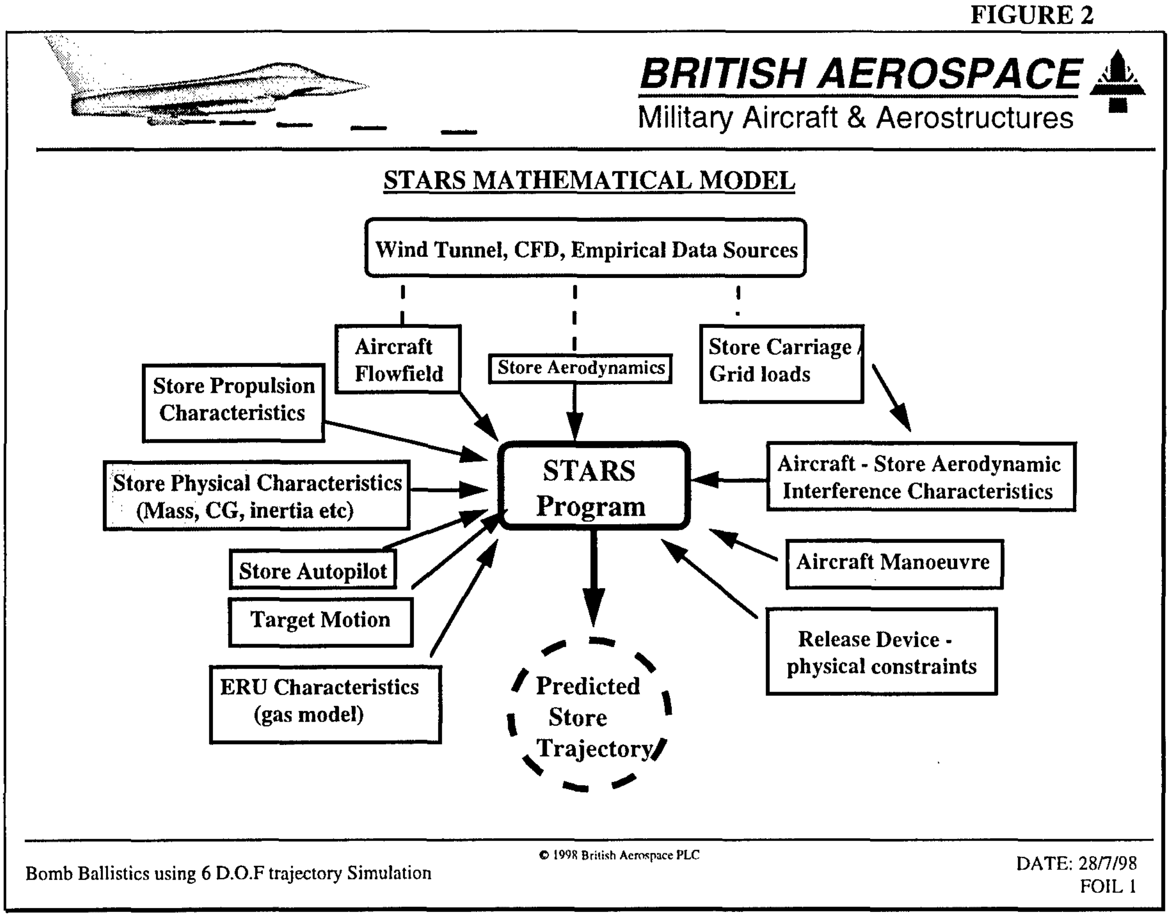


FIGURE 3

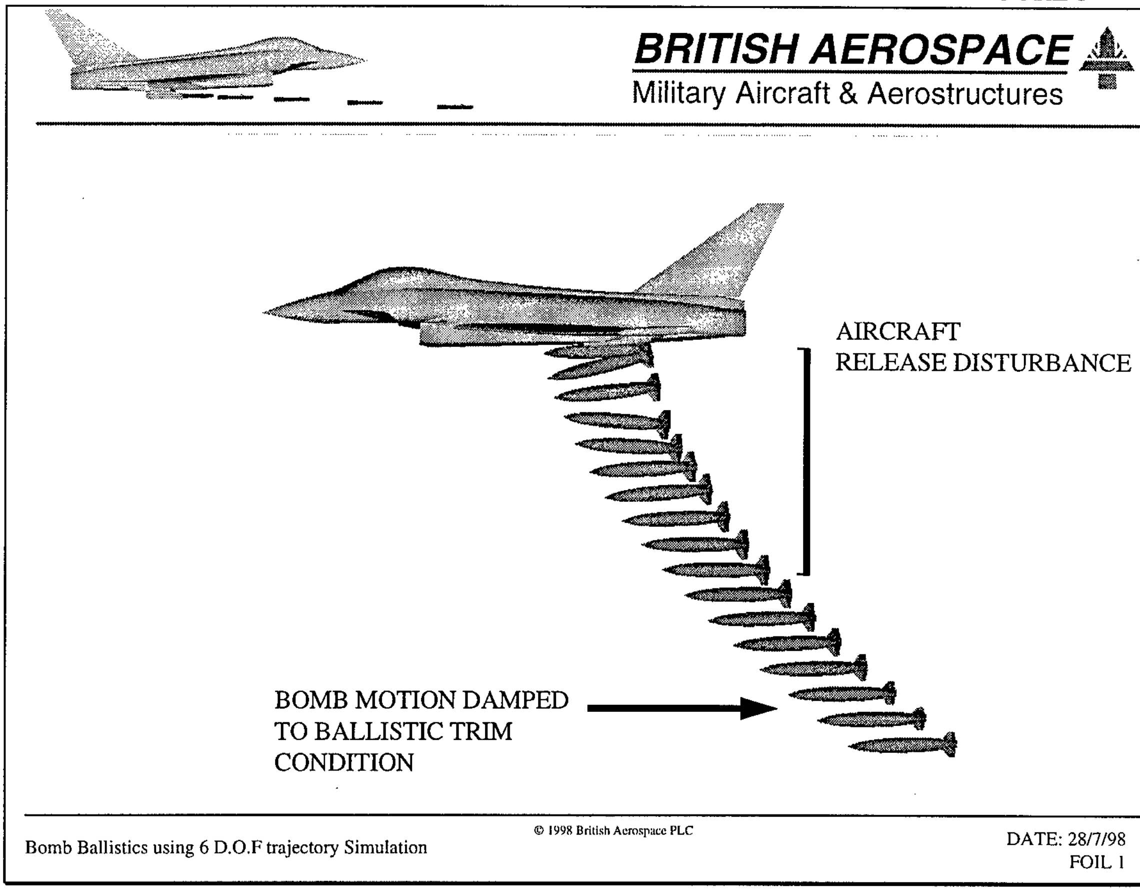


FIGURE 4

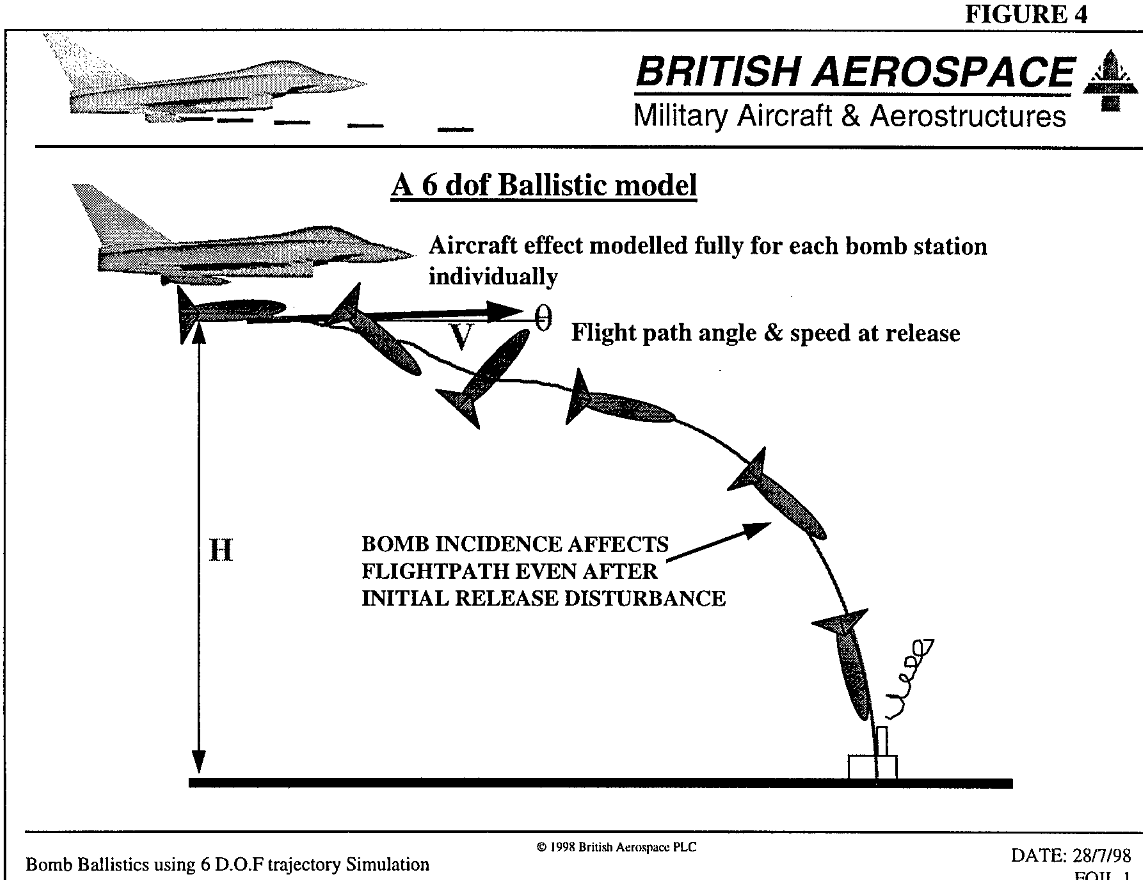


FIGURE 5

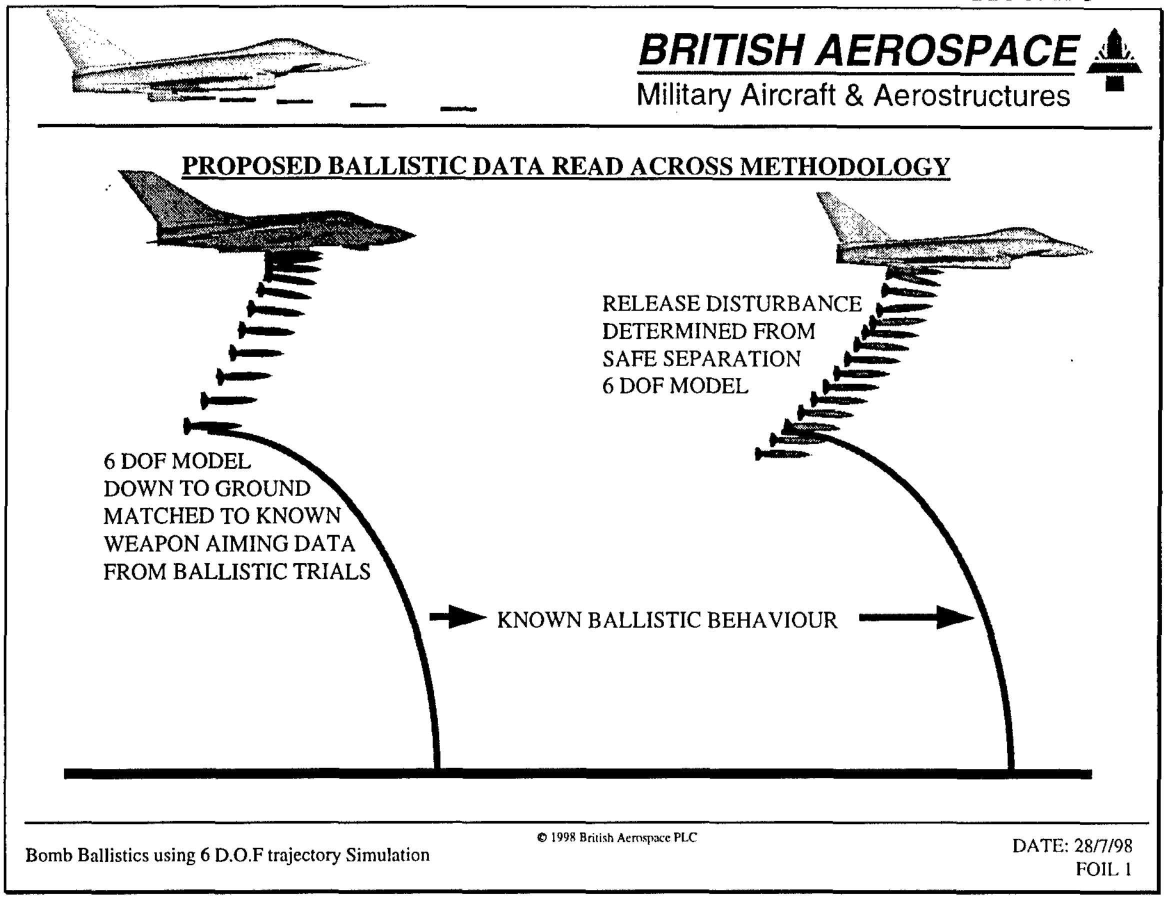


FIGURE 6

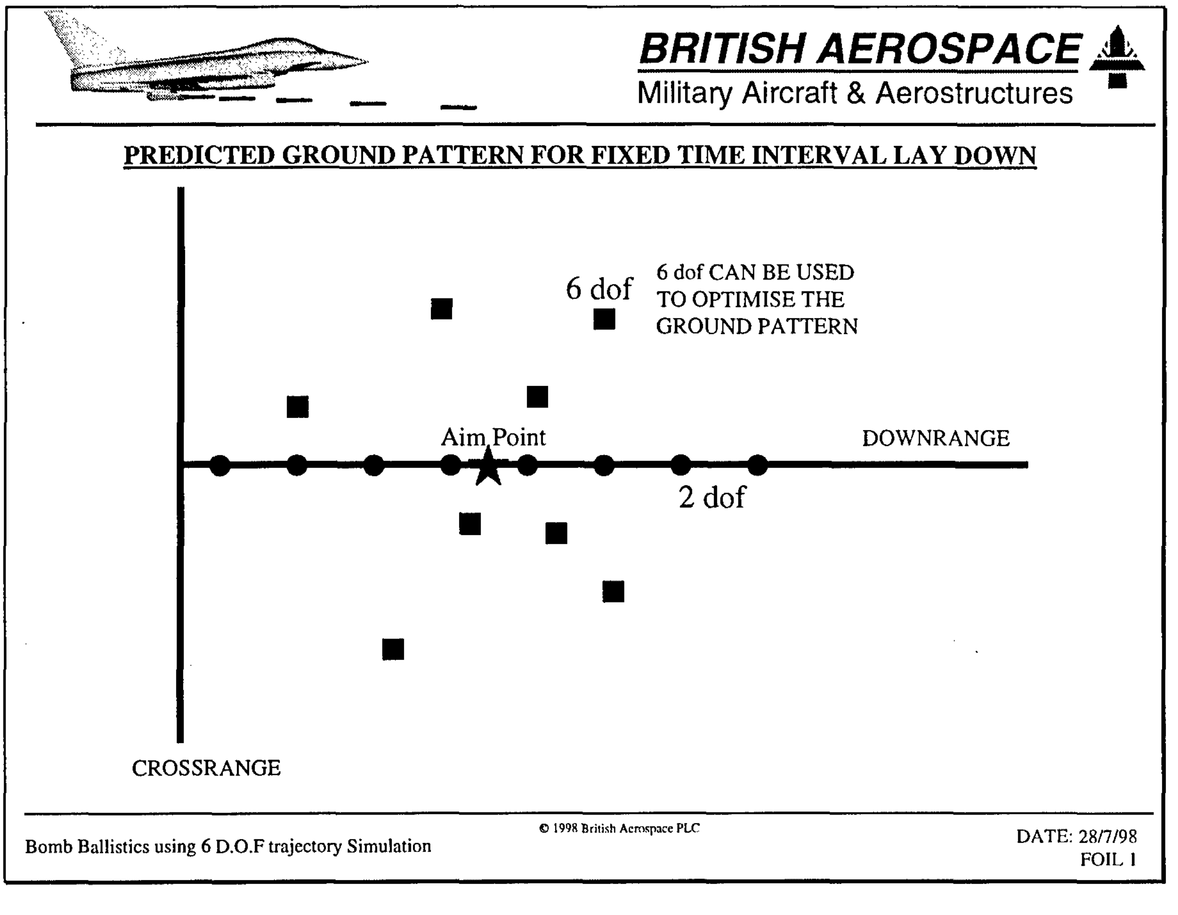


FIGURE 7

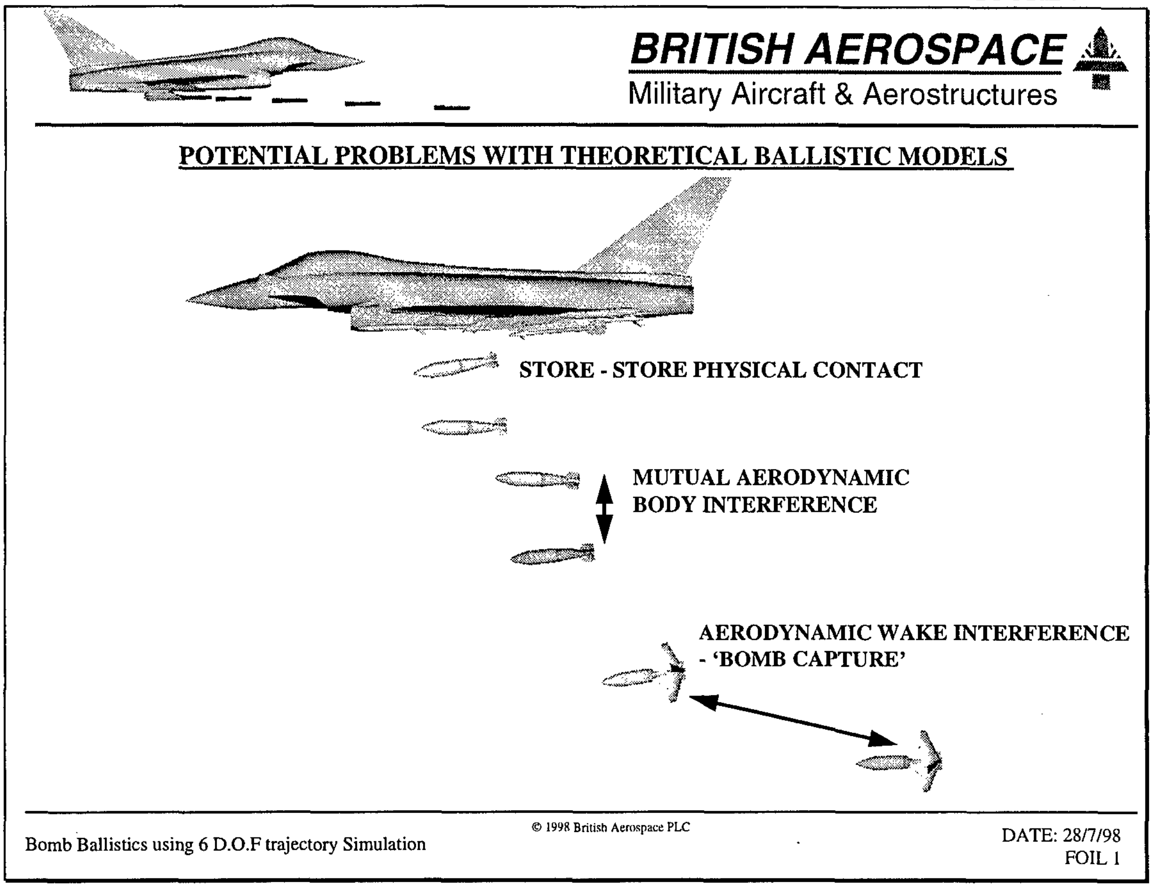
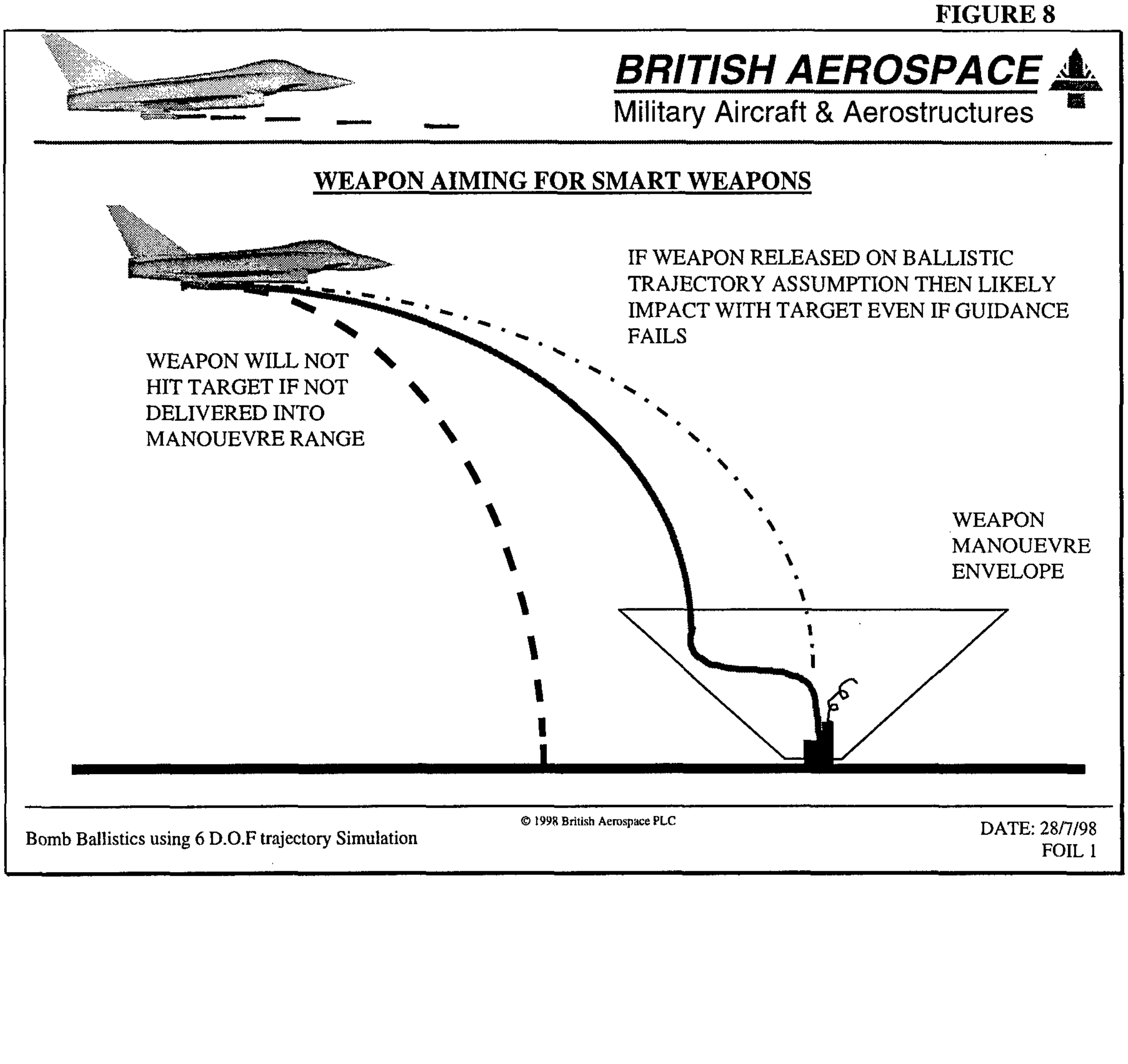


FIGURE 8



Pressure Measurements on a F-18 Wing using PSP Technique

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1. SUMMARY
Surface pressure measurements on a 6% scale model of the F-18 have been carried out at the Institute for Aerospace Research 1.5m x 1.5m Trisonic Blowdown Wind Tunnel using the pressure sensitive paint technique. Model configurations included (1) clean wing; (2) external fuel tanks with empty outboard pylons and (3) external fuel tanks with two MK-83 and vertical ejection racks on the outboard pylons. In this investigation, pressure data on both the upper and lower wing surfaces as well as over the stores were obtained.

The test was performed at a mean chord Reynolds number of 4×10^6 and at Mach numbers ranging from 0.6 to 0.95. The angle-of-attack of the model was set at 0° and 4° nominally with leading and trailing edge flap angles at 0°. Detailed quantitative pressure distributions on the model wing surfaces were obtained. Effects of paint surface conditions and temperature variations on the accuracy of the measurements were assessed and are discussed here. The images obtained using the pressure sensitive paint technique also served as a very indicative flow visualization tool.

2. INTRODUCTION
Surface pressure measurements on a 6% scale model of the F-18 have been carried out earlier at the Institute for Aerospace Research (IAR) using miniature fast response pressure transducers embedded on the wing surfaces (Ref. 1). The high cost of model manufacturing, complex transducer installation procedures have made the technique used in Reference 1 prohibitively expensive. This is especially true when detailed pressure distribution is required and therefore large amounts of transducers have to be installed.

The recently developed pressure sensitive paint (PSP) technique (Ref. 2) is attractive for surface pressure measurements without the need for elaborate sensor installations. The technique used is referred to as radiometric imaging or luminescent intensity method. It has been widely used in a number of establishments (Ref. 2-5) and is considered relatively simple in its application. A preliminary assessment of the radiometric technique as applied in the IAR 1.5m x 1.5m Trisonic Blowdown Wind Tunnel recently on a F-18 model was carried out earlier (Ref. 6). This paper expands on the previous findings and includes additional results on the pressure distributions over an external fuel tank at the transonic regime.

3. TEST FACILITY
The measurements were carried out in the IAR 1.5m x 1.5m Trisonic Blowdown Wind Tunnel. This facility has transonic capability and can achieve a maximum Mach number of 4.25 in the supersonic region as well. The facility may be operated through a range of stagnation pressures at fixed Mach number, thus allowing independent variation of Mach and Reynolds numbers. The transonic test section was used in this test program, with its ventilated walls set at 4% porosity. The walls of the test sections are perforated with 0.5" (12.7mm) diameter holes inclined at 30° to the flow direction, which allow pressure and flow communication between the test section and the plenum chamber.

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

For subsonic and transonic operation, the wind tunnel is equipped with a Mach number control system composed of hydraulically driven chokes that protrude into the flow through the floor and ceiling downstream of the test section. The adjustment of the re-entry flaps at the diffuser entry area which influence the flow out of the plenum chamber is used to control Mach number in the range of $0.95 \leq M \leq 1.2$. An accuracy of ±0.003 in Mach number can be maintained for each blowdown. The stagnation pressure can be kept constant to an accuracy of ±0.03 psi through out the duration of a typical wind tunnel run. A detailed description of the facility with performance tables is given in (Ref. 7).

4. MODEL AND INSTRUMENTATION

The 6% scale of the F-18 model consists mainly of three major parts. They are: an aluminum alloy nose section with integral leading edge extension (LEX) and a single place canopy, a stainless steel centre fuselage with integral wings, and a stainless steel rear fuselage. The centre fuselage is bored to accept a 1.5" (38.1mm) diameter internal strain gauge balance. The model was sting mounted using the support brackets attached to the test section roof. A schematic of the model mounted in the wind tunnel test section is shown in Figure 1. For lighting and cameras, forty window ports with a diameter of 2.625" (66.68mm) are distributed on the tunnel floor and ceiling. They are represented by the circles shown in Figure 1. Fifteen similarly sized window ports have been installed on each of the tunnel sidewalls as well, but were not used during the present test.

Leading and trailing edge flaps and the horizontal stabilators of the model were all set to 0°. Boundary layer transition trips made up of rows of epoxy cylinders (0.05mm high) were installed 0.4" (10.16mm) behind the leading edge of the wings, LEX, engine intakes, vertical tails and horizontal stabilators, on both surfaces. In addition, a ring of transition trips was applied around the nose, and a longitudinal row was fixed in the under fuselage centreline from the nose to the intakes' station. The model was instrumented with static pressure taps at various locations of the nose section, LEX and the canopy. Electronically Scanned Pressure (ESP) modules were used to measure pressure from these conventional pressure taps. An additional sixteen static pressure taps (0.368mm ID), eight on the upper surface and eight on the lower surface, were put on the port wing for the current investigation. They were used primarily as reference pressures for PSP in situ calibration. Figure 2 shows the locations of the static pressure taps on the upper surface of the port wing. Note that all dimensions are in inches relative to model aircraft's absolute origin.

A six component internal strain gauged balance was used to measure forces and moments of the model. Since the model was held stationary during the test, only point measurements were obtained. However, direct comparison in measured forces and moments can still be made for PSP on and off cases.

It is well known that PSP is also quite sensitive to temperature variations. The surface temperature of the starboard wing was measured using an Agema Thermovision 900 thermal imaging system. This system uses a HgCdTe detector with a Stirling cycle cryogenic cooler for efficient operation in the 8-12 micron waveband. The camera employs two scanning mirrors and two integrated temperature calibration blackbodies combined with an on board 12 bit digitizer to achieve a basic accuracy within 1° C. and a sensitivity of .08° C. A wide angle lens having a field of view of 40 x 20 degrees was used for this experiment. The camera was housed in a pressure vessel to protect it from the static pressure and transient temperature environment of the wind tunnel. The pressure vessel was mounted in the test section plenum chamber on the backup structure of the tunnel ceiling. It was necessary to image the object through two anti-reflection coated germanium windows, one in the pressure box and one in the tunnel ceiling. Due to difficulties in

aligning the camera and windows, some vignetting of the image is apparent. The starboard wing of the model was painted with black enamel in order to increase its emissivity. The acquisition of the thermal image on the starboard wing was synchronized with the acquisition of the PSP data from the port wing. The 272 x 136 pixel images were recorded on the hard disk of the Thermovision 900 and then transferred via Ethernet to a PC for analysis using MATLAB. A detailed system calibration was not performed but comparison of the image data with a lab thermometer indicate that the system accuracy including the paint, windows and camera was within 1° C over the range encountered in the experiment.

5. PSP APPLICATIONS AND SETUP

The PSP part of the work was contracted out to a company which provided "turn key" type of operation and services. The PSP method used is widely referred to as "luminescent intensity measurement" or radiometric measurement. The model surface was thoroughly cleaned with alcohol to remove any traces of oil or dust particles prior to application of a white primer. PSP was applied to the port wing surfaces of the aircraft model only, which is of main interest in the current investigation. Two external store models, a 330-gallon fuel tank and a MK-83 general-purpose bomb were painted with PSP at the same time. The inboard and outboard pylons, vertical ejection rack, an assortment of external stores and the port vertical tail were all painted with flat black spray paint in order to minimized unwanted reflections. PSP was applied in situ and over the transition trips. The presence of PSP reduced sharp edges of the trips, which may have to some extent, compromised their effectiveness. Figure 3 shows the model in the wind tunnel after the PSP application.

Eleven blue light emitters were installed inside the plenum chamber with five lights positioned in the ceiling and six in the floor. Two scientific grade CCD cameras were used, one located in the ceiling and the other located in the floor. The forty window ports in the tunnel ceiling and floor allowed a fair amount of combinations for the best choice of camera and light source positions.

6. TEST PROGRAMME

The measurement was performed with the model set at either 0° or 4° for each wind tunnel blowdown. There is about a half a degree sting deflection due to aerodynamic loads at wind on. Data was obtained for Mach number ranged from 0.6 to 0.95 at 0.05 increments. With the Mach number control system, each blowdown consisted of run conditions of two Mach numbers in sequence while maintaining a constant Reynolds number of 4×10^6 based on model mean chord.

A set of runs was carried out prior to the PSP application to serve as baseline measurements for comparisons. Measurements included internal strain gauge balance for the overall forces and moments of the model aircraft, static pressure at various locations of the model as well as the sixteen new pressure taps on the port wing.

PSP testing was carried out at the same run conditions as the baseline runs. Beside the clean wing configurations, runs with external stores were carried out. Seven model configurations at each Mach number and angle of attack of interest were tested. Figure 4 shows the schematic of the various stores configurations. Actually, there are only three different model configurations. The additional configurations were included to minimize unwanted reflections at area of the model that are of interest.

Infrared images of the starboard wing upper surface were obtained at some of the run conditions. These images provide a measure of the temperature variation over the model wing surface during a wind tunnel blowdown.

7. RESULTS AND DISCUSSION

The effect of model surface finish is one of the major concerns with respect to the accuracy of

In general, there is an increase in the forces and moment with the PSP on. There is about one to three percent increase in normal force and pitching moment. Similar increase in magnitude is observed in axial force for M = 0.6 and 0.7. There is, however a much bigger (over 8%) increase in axial force at M = 0.8 with the PSP on.

This comparison is by no means exhaustive and conclusive. However, the results do show that the presence of PSP on the model does change the balance measurements. This is to be expected due to the differences in the surface finish mentioned before. It should be pointed out that the forces and moments measured are at the low end of the balance capacities and within the expected accuracy of the measurement system. A more in depth investigation should be carried out to quantify the effect.

7.3 Reference Pressure Taps Error

An ideal static pressure tap should be of sharp edge and small enough to minimize measurement error. A typical static pressure tap on metal model surface used in IAR is shown in Figure 8. The tap has an inside diameter of 0.0145" (0.37mm). A close examination between the reference static pressure tap of Figure 5, which has PSP applied over it, and the typical pressure tap of Figure 8 reveals that the orifice geometry is quite different. Sufficient (from experience) back pressure was applied through the ESP module when the primer and PSP were sprayed onto the model surface to avoid blocking of the reference pressure taps. After the PSP had been cured, the resulting orifice geometry was no longer perfect as can be seen in Figure 5, having an appearance of a funnel with a rounded edge. It is pointed out in Reference 8 that an orifice having a radius edge would introduce a positive error in the static pressure measurement. The magnitude of the error would amount to 1.1% of dynamic pressure if the radius of the edge equals that of the orifice inside diameter. As mentioned before, some baseline runs were carried out prior to PSP application to the model. Comparisons of the static pressure obtained using ESP module on the model forebody, which is not painted, for the baseline runs and PSP runs show excellent repeatability. The variations in C_p is about 0.1% for both M = 0.6 and M = 0.8 cases. Similar comparisons were carried out for the measurements obtained from the port wing reference pressure taps. The measurements from the PSP runs (using ESP data) show a consistent higher static pressure obtained from the same pressure taps of the baseline runs. The variation between the baseline runs and the PSP runs is about 2% in C_p. Table 2 shows the effects of the presence of PSP on static pressure measurement on the model. Only results from a sample of the pressure taps are shown and only for M = 0.6 and $\alpha = 4.5°$ as the observations are very similar for other conditions.

Tap No.	Forebody tap (Cp) (Not Painted)		Port wing tap (Cp)	
	PSP off	PSP on	PSP off	PSP on
1	0.0073	0.0060	-0.3030	-0.2865
2	-0.0023	-0.0028	-0.3263	-0.3093
3	-0.0045	-0.0050	-0.3288	-0.3098
4	-0.0110	-0.0108	-0.2723	-0.2445
5	0.0030	0.0010	-0.1040	-0.0835

Table 2 Effects of PSP on Pressure Tap Measurements (M = 0.6 and $\alpha = 4.5°$)

There is no doubt that part of the errors observed is due to changes in the orifice edge geometry by the presence of PSP.

7.4 Temperature Effect

In situ calibration of the intensity ratio was carried out for each scan to account for temperature change between the run and the wind-off reference image. The uncertainty of this calibration is about ±4% in C_p on the average. It should be noted that this calibration is based on the reference static pressure, which is affected by the presence of PSP as discussed above. In addition, this calibration can

quantitative PSP measurements. There is also a relatively large transient temperature change during start up of a blowdown wind tunnel. Static temperature variation over the wing is also a concern. These effects will be discussed in the following section. Comparisons between PSP data with previous conventional pressure transducers measurements and CFD predictions are provided as well.

7.1 Surface Finish

Surface finish of a small-scale wind tunnel model is critical to accurate aerodynamic measurements. With the advent of modern day numerically controlled machines, trained model makers can achieve a very high tolerance. At IAR, the typical model surface finish is better than or equal to 8μ inches rms. Application of PSP on model surface is done manually using an air brush. This task is carried out by an experienced technician as well. However, application of PSP on an aerodynamically smooth model surface will always present some uncertainty about its effect on the model surface and, consequently, the pressure measurements.

Figure 5 shows a close up image of part of the painted model area. The dark circular disk is one of a series of markers deposited at precisely known location on the model surface. Also shown in this figure is one of the reference static pressure taps on the wing surface. The nominal orifice internal diameter is 0.0145" (0.37mm). The image was taken after approximately 180 blowdowns and as can be seen, the paint surface is contaminated with quite a lot of dust particles. It should be pointed out that the PSP part of measurement was carried out during the initial 50 blowdowns of the wind tunnel programme only. Due to the rubbery nature of the paint finish, it was not possible to clean the model surface as a routine practice. Figure 6 shows the PSP finish on a sample coupon, which was painted at the same time as the F-18 model. It provides an indication of the painted model surface condition before any deterioration or contamination due to usage.

The uniformity of the paint thickness was investigated. A coordinate measuring machine with a quoted accuracy of ±0.0002" (±0.005mm) was used to survey the wing surface at two spanwise locations. The survey was carried out with the PSP on and then repeated at the same location with the PSP stripped off. Over a thousand samples were collected for each survey. Figure 7 shows a plot of the PSP thickness over the length of the chord at the two spanwise locations on the wing upper surface. The mean thickness of the paint including the primer is about 0.0015" (0.038mm) with a standard deviation of ±0.0002" (±0.005mm). The presence of PSP on the model surface changes the profile of the model. This should be taken into account when evaluating the accuracy of PSP measurement. The painted surface is quite different in texture from the metal model surface, which is usually polished to a mirror finish. The boundary layer growth over these two surfaces will be different and will lead to different pressure distributions.

7.2 Effects of PSP on Balance Measurement

Comparisons were made of the model forces and moments obtained for the PSP on and off cases. The results are given in Table 1. Only normal force, pitching moment and axial force coefficients are compared, as the other terms are quite small in magnitude. It should also be pointed out that only the port wing was painted with PSP and not the complete model.

M	PSP	CN	CM	CX
0.6	Off	0.257	0.0189	0.0130
	On	0.260	0.0192	0.0133
0.7	Off	0.275	0.0193	0.0125
	On	0.283	0.0196	0.0129
0.8	Off	0.303	0.0218	0.0116
	On	0.307	0.0225	0.0126

Table 1 Effects of PSP on Balance Measurement

not account for local temperature variation on the model surface.

During a typical run of about 30-sec. duration for a blowdown wind tunnel, the stagnation temperature will drop by as much as 6 °R due to flow expansion. There is also a very high temperature transient, up to 30 °R, at the start up of the wind tunnel, but that lasts for only a short duration. Figure 9 shows a typical time history of the wind tunnel stagnation temperature. The start-up temperature transient is quite prominent and the stagnation temperature stabilized towards the end of the wind tunnel blowdown. The sudden drop in temperature occurred when the control valve moved to set another Mach number condition during the same blowdown. In this particular run four wind on scans of PSP data were obtained, two for each Mach number. It has been shown that there is quite a large thermal effect for pressure sensitive paint (Ref. 9). Without proper thermal compensation, this is a major source of errors to the PSP measurements.

As mentioned before, each wind tunnel run can be programmed to establish two constant Mach numbers, one after the other, at a constant Reynolds number. Each blowdown has a useful run time of about 10 to 15 seconds for each Mach number. Up to four PSP images can be taken during each constant Mach number run, but most of the runs have only two PSP images taken to save wind tunnel time. Figure 10 shows the pressure distributions on the upper surface of the wing at 65% spanwise location. The run condition is M = 0.6 and the model angle of attack is 4.5°. Pressure data were extracted from four PSP measurements (images) taken at about 4 seconds apart. Scan 2 refers to the first wind-on PSP measurement with scan 1 being the wind-off reference image. The scan to scan repeatability is very good from 20% chord to about 60% chord. Towards the wing trailing edge, there is a drastic variation in the deduced pressure among scans. As the blowdown continues, from scan 2 to scan 5, the surface pressure close to the trailing edge tends to collapse to an equilibrium value. The variations observed are attributed to temperature effects. It has been pointed out before that the stagnation temperature varies during a blowdown with a large transient at the start up of the tunnel. It is obvious that the PSP image acquired during the first wind-on scan is still very much affected by the rapid changes in temperature transient. Close to the trailing edge of the wing, the section there is quite thin compare to the main wing section. The heat transfer rate is expected to be different at the wing main spar and the trailing edge. The trailing edge would react to temperature variations faster than the thicker wing section. The same would be true for the wing tip and the thin section of the leading edge. For comparison purpose, results from previous wind tunnel data obtained at similar conditions (Ref. 1) using Kulite pressure transducers are included in this Figure. Results from a transonic small disturbance code, KTRAN (Ref. 10) are also shown. The agreement between PSP and the conventional pressure transducers measurements is not good. The discrepancy is probably due to a combination of temperature effect, reference pressure taps geometry error and different surface finish. The PSP image for this case is shown in Figure 11 for reference. The changes in the colour contours are quite gradual with the exception of the wing leading edge. This shows up as the sharp suction peak in Figure 10.

Figure 12 shows the variations of static pressure on the wing upper surface between scan 5 and scan 2 of the run discussed above. The image is reconstructed by taking the differences between the images of scan 5 and scan 2. It can be seen very clearly that at regions where the model sections are thin, near the wing tip and trailing edge, biggest variations in measured pressure are observed. It should be pointed out that the Mach number and stagnation pressure in the tunnel was maintained constant between scan 2 and scan 5. There is, however, a change in the stagnation temperature as mentioned before. Figure 13 shows a similarly

reconstructed infra red image of the starboard wing obtained in the same wind tunnel condition. It shows clearly that there is quite a large temperature variation, up to 5 °C, during the run on the thin parts of the wing planform. This infrared image correlates very well with the reconstructed PSP image (Fig. 12).

Figure 14 shows the pressure distributions on the same wing location for M = 0.65 case, for both the upper and lower surfaces. The data was obtained as the second portion of the same wind tunnel run. The stagnation temperature variation is much more gradual during this portion of the run, less than 2 °R in 15 seconds. The repeatability of the pressure distribution is very good for the four PSP scans. There are still some minor variations of C_p at the wing trailing edge where the section is the thinnest.

The above comparisons demonstrate very well that the type of PSP method employed, luminescent intensity measurement, is affected quite severely by thermal effect. However, for moderate changes in temperature, the effect on pressure measurement should be within the measurement accuracy.

7.5 PSP Technique as Quantitative Pressure Measurement Tool

Selected results obtained from the PSP measurements over the wing of the F-18 model are given below. Since it has been observed that the wind tunnel start-up transient temperature has a big effect on the accuracy of the PSP measurement, only the last scan of each run is used for all subsequent data analysis.

Figure 15 shows the pressure distributions over the wing section at 47% spanwise location for M = 0.6. The estimated correction due to orifice geometry is included. With the correction applied, the measurement is closer to the conventional pressure transducers measurements. However, the comparisons are not very good at the upper surface near the mid-chord section. The agreements are much better near the trailing edge for both the upper and lower surface measurements. One of the deficiencies of the PSP measurement is the erroneous result obtained at the extremities of the image. The sudden rise in pressure at the wing trailing edge as deduced from the PSP is probably due to a combination of non-ideal camera angle and lighting, model motion and image alignment. Results from CFD code KTRAN are also included in this figure for comparison.

Similar results and comparisons are given in Figures 16 and 17 for M = 0.8 and 0.9 respectively. With the exception of the leading edge region on the lower surface, the agreements between the two sets of measurements are quite good for the M = 0.8 case. There is no comparable KTRAN and conventional pressure transducer results for M = 0.9 and results from an Euler code FJ3SOLV (Ref. 11) is included instead for comparison. The initial weaker shock located at 17% chord (Fig. 17) is fairly well predicted. The Euler code predicts the stronger shock at about 65% chord, which is further back than indicated from the PSP measurement. This is to be expected, as there are no viscous effects included in the Euler code. It is also not clear what effects the PSP would have on the formation of shock waves. Other than the shock position, the agreement is quite good between PSP measurements and the Euler code prediction. It should be noted that the critical C_p for this run condition is –0.2. Figures 18 and 19 show the PSP images of the wing upper and lower surfaces respectively for the case considered above. The run conditions are M = 0.9 with model angle of attack at 4.5° for the clean wing configuration (Config. 1).

Figures 20 and 21 show the pressure distributions on the wing upper and lower surfaces as depicted by the PSP images. A 330 gal. external fuel tank (EFT) was mounted inboard and the outboard pylon was empty. Freestream Mach number was 0.9 with the angle of attack at 4.5°. The pressure distributions at the middle of the lower surface of the fuel tank were extracted and comparison made

is in addition to the ±4% uncertainty in C_p due to the calibration.

Temperature has a significant effect on the luminescent intensity PSP measurement. This is especially evident on thin sections of the model. However, useful data can be obtained once the tunnel start up transient is over. For this particular model with the thinnest section less than 0.1" thick, a further delay of 2 seconds after the flow established is sufficient.

Good comparisons with conventional pressure transducer data are obtained for M = 0.8 at angle of attack of 4.5°, but not so good for M = 0.6 case at the same spanwise location. There is also quite reasonable agreement with predictions from CFD codes.

PSP technique and the images generated serve as a very useful and indicative flow visualization tool. Shock waves and their locations can be readily recognized on the model surface. Complex flow patterns generated by various model parts are readily visible. These will provide valuable information to guide further development of computational codes.

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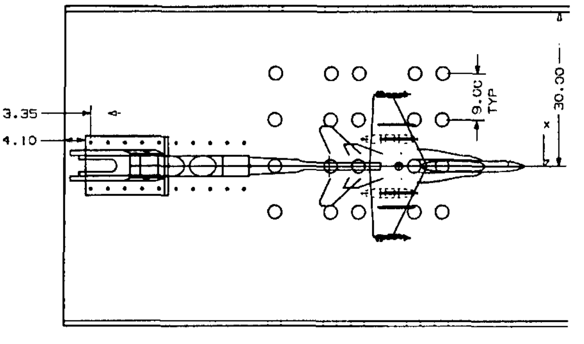

Figure 1: Schematic of Test Setup (Top View, All Dimensions in Inches; Circles Denote Window Ports)

with the Euler calculation (Fig. 22). The agreement between the PSP measurement and CFD prediction is quite good. There is again the discrepancy in the shock position and it is believed that viscosity effect is the primary cause of it. Comparison is also made of the pressure distributions for the same test condition but at a different location on the wing. Figure 23 shows the pressure distributions obtained at 47% spanwise location on the lower surface of the wing. This spanwise position is located between the fuel tank and the outboard pylon. The PSP measurement compares quite well with the Euler prediction with the exception of the shock strength and location.

7.6 PSP Technique as Flow Visualization Tool

The flow characteristics over the wing surface are very clear and indicative. On the upper surface (Fig. 18), a well defined shock wave starting from the wing leading edge junction with the leading edge extension (LEX) can be clearly seen. The flow passing through the gap of the inboard and outboard leading edge flaps shows up clearly as well. The flow downstream of the normal shock wave, located at about mid chord, is fairly uniform. There is a rather complex and interesting flow region near the wing tip area with the merging of the flow from the tip missile and launcher and the coalescence of the two shock waves. There is not much evidence of the weaker shock wave from the nose of the tip missile. The shock wave originating from the junction of wing tip and the missile launcher can be seen clearly. On the lower surface (Fig. 19), a high pressure region can be seen at the wing leading edge. This region extends further downstream inboard of the wing than outboard of the wing. The compression (red spot) and expansion regions (blue spots) of the wing fold mechanism fairing at about 70% wing span can be seen clearly as well. Localized flow expansion due to the presence of fins of the tip missile and the engine intake show up as low pressure regions.

Similar PSP images are shown for model configuration 7 in Figures 20 and 21. The run conditions are the same. There is a 330 gal. EFT mounted on the inboard pylon with the outboard pylon empty. The pylons were painted flat black to avoid reflection. This accounts for the false colour regions of Figures 20 and 21. The flow features over the wing upper surface are very similar to that of the clean wing configuration (Fig. 18). The location where the two shock waves coalesce is slightly more inboard. On the lower surface of the wing, the presence of the EFT and the empty outboard pylon alter the flow patterns substantially as would be expected. A much lower pressure regions can be seen between the EFT and the pylon at the mid chord location. Similar features can be seen between the EFT and the model fuselage. These are due to the accelerated flow between the appendages.

8. CONCLUSIONS

Pressure sensitive paint technique was used on a 6% scale F-18 model and tested in the IAR 1.5m x 1.5m Trisonic Blowdown wind Tunnel in the transonic regime.

The application of the PSP to the model surface added about a 0.0015" (0.038mm) thick layer to the model. This extra layer of paint modifies the model profile and is especially important in the thin section regions like the wing trailing edge and wing tip. Surface finish of the PSP on the model is not as smooth as the bare metal counter part. The silicone based PSP painted surface is also very easily contaminated by dust particles in a blowdown wind tunnel environment. The presence of the PSP on the model surface changes the surface texture, which changes the boundary layer transition location and introduces additional drag. A more in depth investigation should be carried out to quantify the effect.

The geometry of reference static pressure orifices is modified by the application of the PSP. The in-situ calibration through these reference pressure orifices will have an additional error built in to the calibration curve due to imperfect orifice geometry. This error is estimated to be about 2% in C_p, which

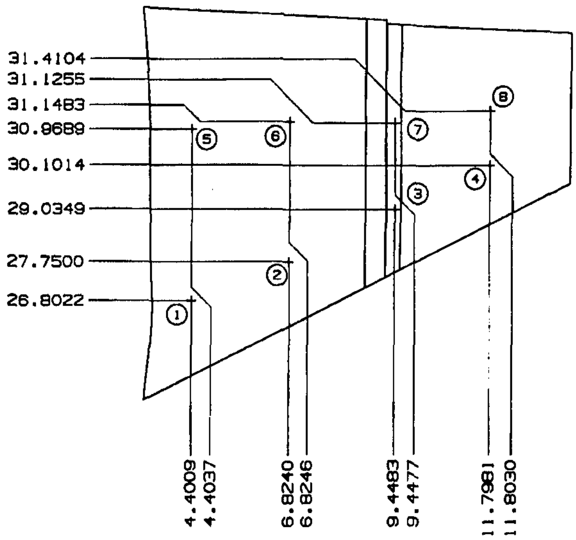

Figure 2: Static Pressure Tap Locations on Wing Upper Surface (All Dimensions in Inches)

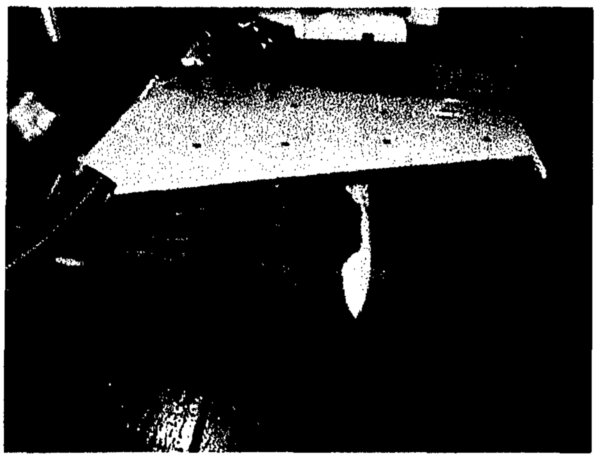

Figure 3: F-18 Wind Tunnel Model with PSP Applied

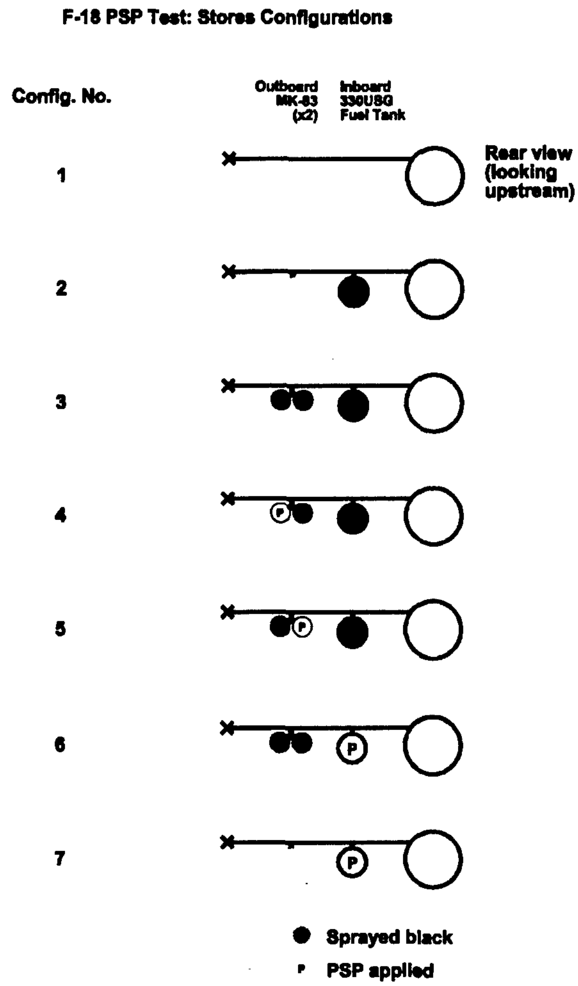

Figure 4: Stores Configurations with PSP and Sprayed Black

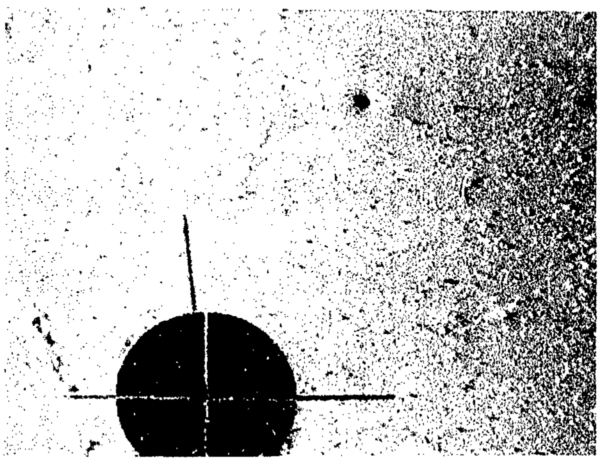

Figure 5: Close Up of Typical PSP Surface after 180 Blowdowns

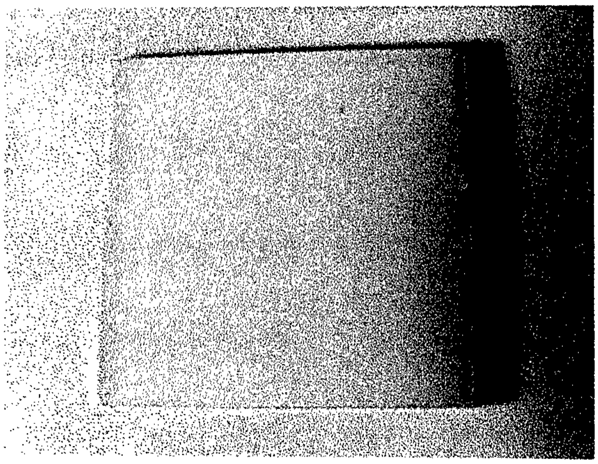

Figure 6: Sample PSP Coupon

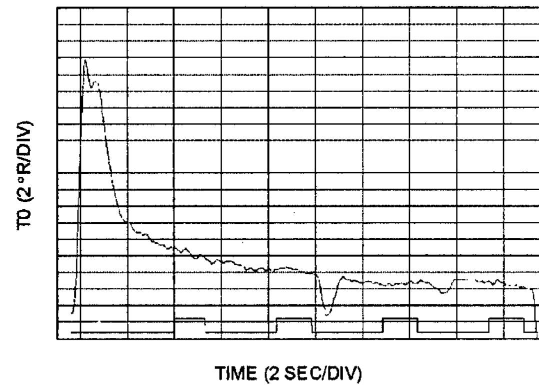

Figure 9: Typical Time History of Stagnation Temperature During Wind Tunnel Run

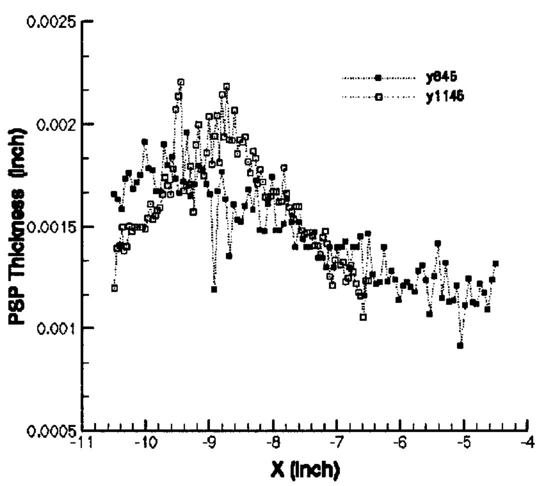

Figure 7: Typical PSP Thickness on Model Surface

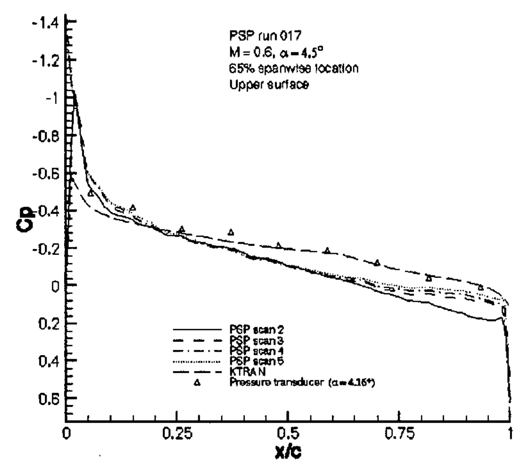

Figure 10: Pressure Distributions on Wing Upper Surface (M = 0.6, 65% Span Location)

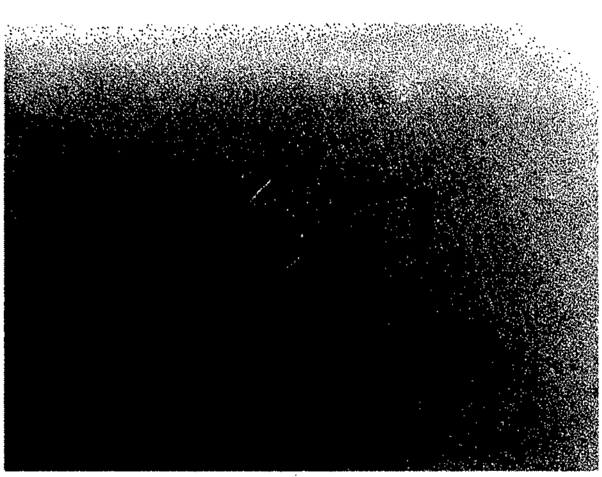

Figure 8: Typical Static Pressure Tap on F-18 Model

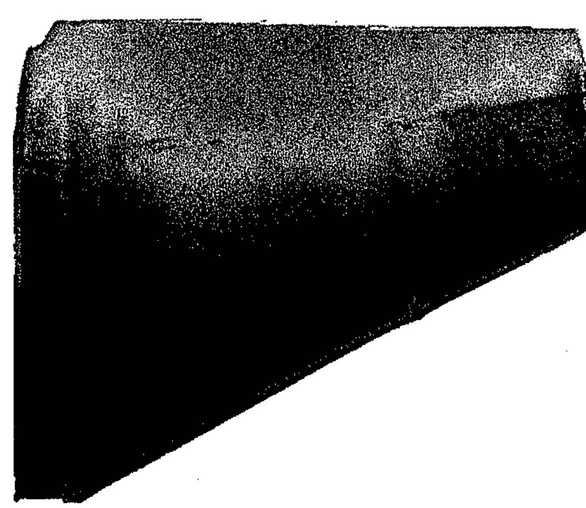

Figure 11: Port Wing Upper Surface PSP Image (M = 0.6, $\alpha = 4.5°$, Config. 1)

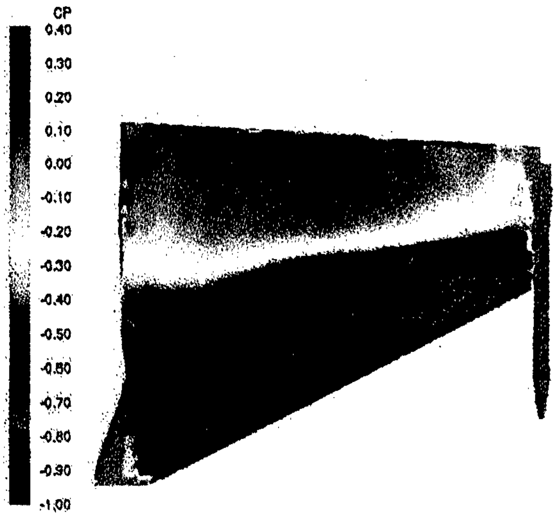

Figure 18: Wing Upper Surface PSP Image (Clean Wing Configuration, M = 0.9, $\alpha = 4.5°$)

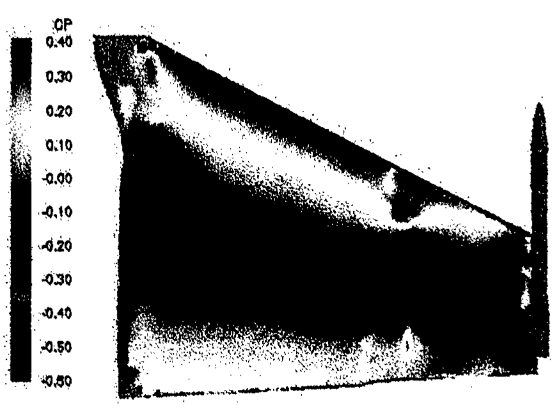

Figure 19: Wing Lower Surface PSP Image (Clean Wing Configuration, M = 0.9, $\alpha = 4.5°$)

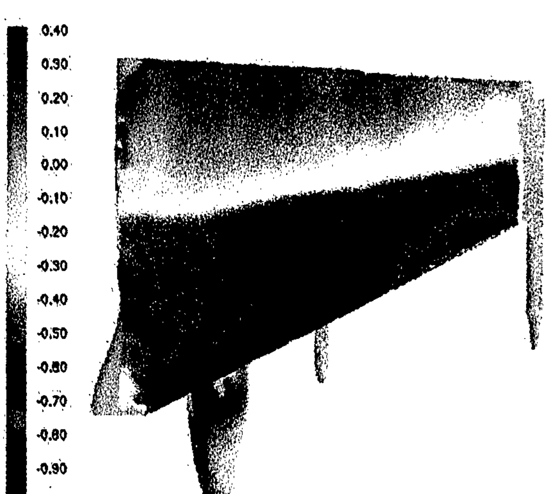

Figure 20: Wing Upper Surface PSP Image (330 USG EFT Inboard, Empty Pylon Outboard, M = 0.9, $\alpha = 4.5°$)

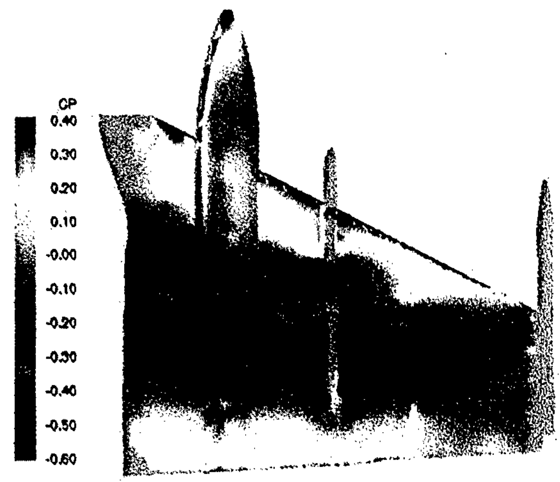

Figure 21: Wing Lower Surface PSP Image (330 USG EFT Inboard, Empty Pylon Outboard, M = 0.9, $\alpha = 4.5°$)

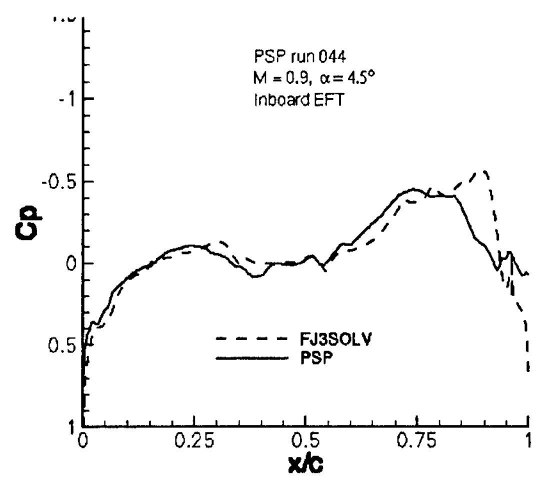

Figure 22: Pressure Distributions over the External Fuel Tank Lower Surface (M = 0.9, $\alpha = 4.5°$)

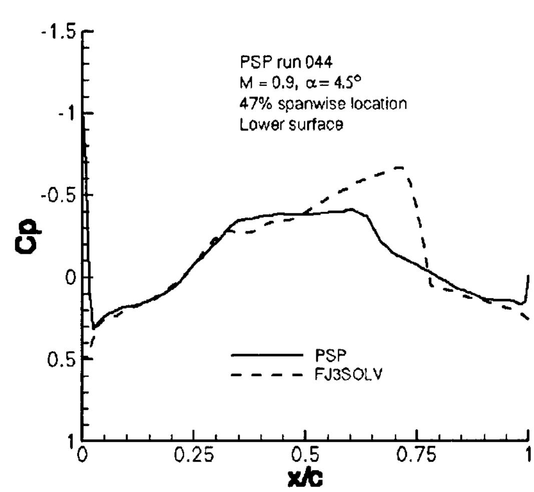

Figure 23: Pressure Distributions over Wing Lower Surface (Config. 7, M = 0.9, $\alpha = 4.5°$)

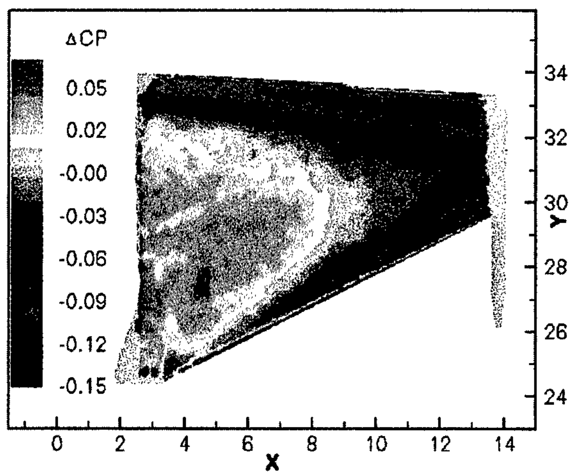

Figure 12: Variations of Static Pressure over Wing Upper Surface between Scan 5 and Scan 2 (M = 0.6, α = 4.5°, Config. 1)

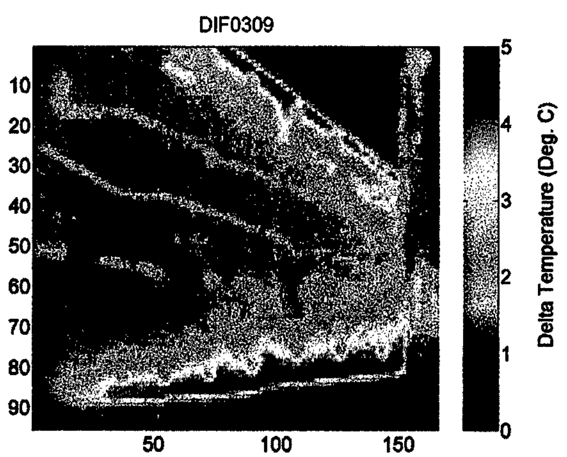

Figure 13: Variations of Local Temperature on Wing Upper Surface between Scans

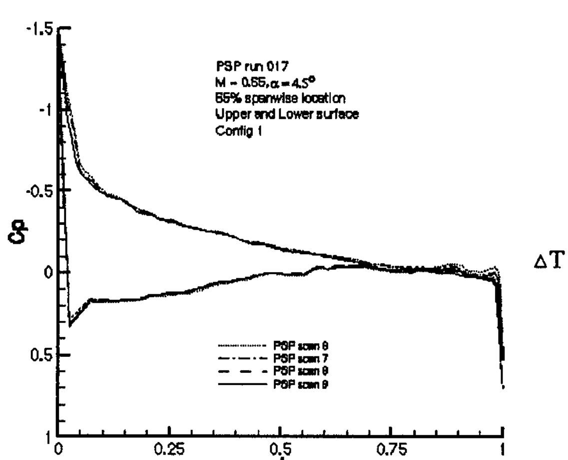

Figure 14: Pressure Distributions on Wing Surface (M = 0.65, 65% Span Location)

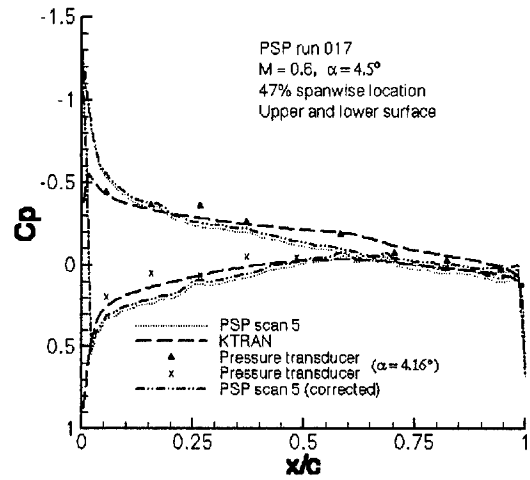

Figure 15: Pressure Distributions on Wing Surface (M = 0.6, 47% Span Location)

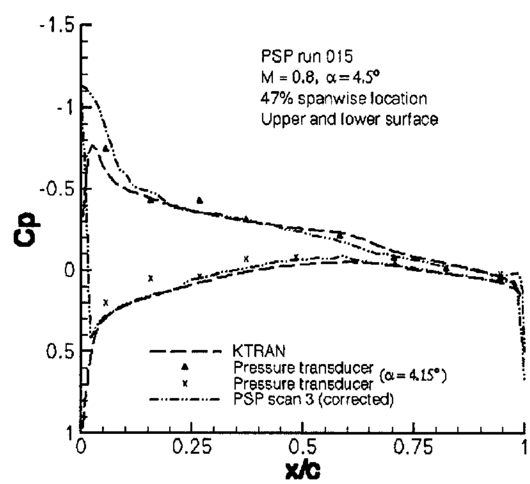

Figure 16: Pressure Distributions on Wing Surface (M = 0.8, 47% Span Location)

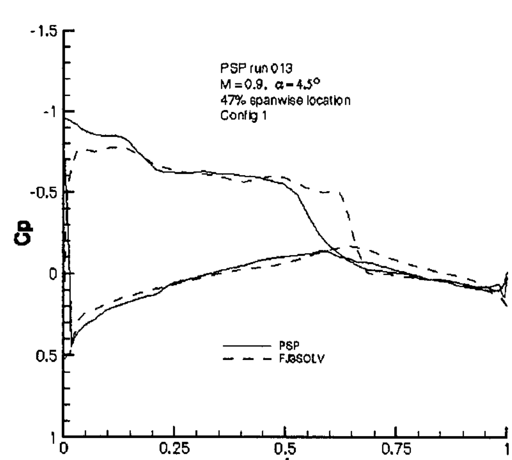

Figure 17: Pressure Distributions on Wing Surface (M = 0.9, 47% Span Location)

NAWCAD Photogrammetrics: Methods and Applications for Aviation Test and Evaluation

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SUMMARY

Photogrammetry using multiple sequential recorded film and video images has been an integral part of flight test and evaluation at the Naval Air Warfare Center Aircraft Division (NAWCAD) at Patuxent River, MD for nearly 40 years. Photogrammetric analysis is used for evaluation of stores separation, carrier suitability, ballistic trajectory tracking, overhead impact scoring, and mishap reconstruction. NAWCAD, Patuxent River, MD recently began flight testing for the F/A-18 E/F development program. The initial phase of the weapons separation portion of the F/A-18E/F development program is a 13 month project consisting of two aircraft flying 256 flights during which 2000 stores will be dropped. To meet the challenge of processing high volumes of photogrammetric data and delivering solutions within 72 hours of each flight, the NAWCAD Photogrammetric Team initiated strategies to reduce the time, increase the volume of data analysis, and increase the accuracies of solution processes that historically have been labor intensive and difficult to present. The NAWCAD Photogrammetric Team is developing an image enhancement and data analysis system, and an on-line database which will provide near real-time access and retrievability of test data. This paper describes how NAWCAD scientists have applied a clearly defined process for photogrammetric efforts, implemented state-of-the-art hardware and software methodologies, and architecture that reduce the turnaround time, reduce the cost, increase the accuracy, and facilitate the delivery of custom-formatted products to the flight test engineer.

Keywords: flight testing, carrier suitability, stores separation, lens distortion, survey, feature tracking, ballistics, photogrammetry, mishap reconstruction, overhead scoring

1. OVERVIEW

Photogrammetric analysis for flight test and evaluation applications provides unique challenges from both a technical and managerial perspective. In designing solution algorithms, photogrammetric analysis must take into account factors such as camera angle, camera movement, film quality, lens focal length and distortion, and environmental conditions. Additionally, flight test and evaluation events occur in environments that are hostile to precise measurements. From a personnel perspective, the photogrammetric configuration involves a broad range of skills. The photogrammetric team includes surveyors who provide measurements on the aircraft and stores, image analysts who read and edit film, electronic technicians who repair and maintain photogrammetric equipment, and mathematicians and software engineers who develop and execute the algorithms that provide photogrammetric solutions. Management must facilitate communication within a team that includes highly technical and analytical processes as well as less technical, hands-on oriented processes.

At NAWCAD, Patuxent River, MD, the primary flight test and evaluation applications for photogrammetric analysis are:

- carrier suitability
- ballistic trajectory measurement
- overhead scoring
- stores separation
- mishap investigation

1.1. Carrier Suitability

Carrier suitability tests are conducted to ensure that the structural integrity of the aircraft is not compromised during carrier take-offs and arrested landings for ship operations while the aircraft maintains acceptable flying qualities and performance. Carrier suitability events are flown on specific operational U.S. Navy aircraft carriers while at sea or at the arrested landing and catapult sites at NAWCAD, Patuxent River, Maryland and Lakehurst, New Jersey. Cameras are mounted at the site of the arrestment landing or catapult launch area (see Figure 1). Photogrammetric analysis provides aircraft position and attitude information for catapult launches, touch-and-go's, and arrested landings.

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

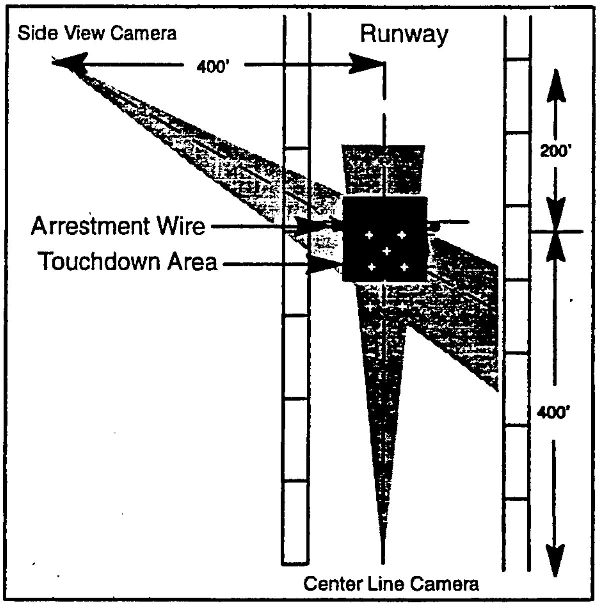

Figure 1. Mark–7 arresting gear camera configuration

1.2. Ballistic Trajectory Measurements

The ballistic trajectory of a store from aircraft release to impact is measured to allow accurate programming of the aircraft store release computer and to determine safe aircraft separation from the store upon store detonation. The Atlantic Test Range (ATR) provides real-time theodolite data processing. To significantly increase the accuracy of the results, photogrammetric analysis methods are used to incorporate boresight corrections to the raw data. The photogrammetric team also provides position tracking of aircraft. Final ballistic analysis also accounts for weather data provided by weather balloons.

1.3. Overhead Scoring

The ability of an attack aircraft to accurately hit a ground target is integral to the success of the mission. For overhead scoring applications, multiple store impacts near surveyed target arrays are scored using film taken from the doorway of an observing helicopter. Miss distances are computed between the splash point and the survey target array.

1.4. Stores Separation

Stores separation tests ensure stores released from an aircraft can safely pass through the aerodynamic perturbation of the aircraft without impacting the aircraft or other stores released simultaneously which can cause damage to the aircraft or premature detonation of the stores. Photogrammetric analysis provides the position and orientation of a store with respect to the aircraft during stores separation. Velocities and rates are also provided using smoothing techniques. To record stores separation events, cameras are mounted directly on the aircraft. Collection of photogrammetric data must overcome a number of unique environmental factors and restrictive test conditions including vibrating cameras, strong sunlight or shadows, vapor trails, and obscured camera views.

1.5. Mishap Reconstruction

Accurate engineering data are vital to the timely resolution of accident investigations. The recording by film or video of many accidents is typically not of the best quality. Creativity and flexibility are required to extract useful results from these sources. The information collected can be animated on a graphics workstation to provide different perspectives of the accident.

1.6. Purpose of Paper

This paper will discuss the process and the management techniques to provide photogrammetric analysis of stores separation events. Additional analysis services provided by the photogrammetric team, with the exception of mishap reconstruction, are subsets of the stores separation process capabilities.

2. STORES SEPARATION FLIGHT TESTING

The design of a store during a weapons development program is determined by operational requirements and wind tunnel and computational fluid dynamics (CFD) data. To validate the wind tunnel and CFD models and to reduce the number of expensive development models expended during flight tests while maximizing the engineering data gathered during flight tests, photogrammetry is used to measure the 6 Degree–Of–Freedom (6DOF) trajectory of the store during and after release from the aircraft. This 6DOF data are used to validate the separation models. The stores separation envelope encompasses the scope of the altitude, airspeed, and dive angle that allow for operational employment of the stores. The edge of the envelope is the final point at which a store can be safely ejected from an aircraft. Without photogrammetry, stores separation flight testing is qualitative in nature and consists of numerous flights that approach the edge of the separation envelope in small, incremental steps. Another photogrammetric specific measurement conducted during stores separation flight testing is the minimum miss distance between a store and the aircraft during the separation event. The miss distance is critical in determining the ability of an aircraft to safely deliver a particular store or configuration of stores.

Cameras attached to the aircraft capture the release of a store or group of stores. As opposed to carrier suitability events where the cameras are mounted on a permanent static

platform at the site of the event, stores separation algorithms must handle data that are obtained from cameras attached to a rapidly moving aircraft. In addition, the cameras themselves are subject to movement relative to the store and aircraft coordinate systems due to wing movement or fluctuation in air flow.

Flight test and evaluation involves processing high volumes of data in a relatively short amount of time. A major ongoing effort at NAWCAD involves the recently developed F/A-18 E/F aircraft. The stores separation portion of the F/A-18 E/F program is a 13 month schedule consisting of two aircraft flying 256 flights during which 2000 stores will be dropped. Six DOF photogrammetric analysis must be provided within three days following a flight. These composite requirements far exceed any previous 6DOF photogrammetric analysis efforts using previous processes. As a result, initiatives were undertaken to upgrade the photogrammetric process.

3. AIRBORNE PHOTOGRAMMETRIC ENVIRONMENT

For flight test and evaluation applications, photogrammetric analysis requires a great deal of creativity in the design and application of solution algorithms. In the case of stores separation, cameras are attached to a flexible aircraft and configured to capture the descent of a store or multiple stores attached to the aircraft. The photogrammetric team has developed solution algorithms to accommodate a variety of conditions, including camera malfunction, camera movement, missing IRIG (International Range Instrumentation Group) time on film, and meteorological conditions. Targets on a store or aircraft can become "washed out" in extreme sunlight making it difficult or impossible to read key points for an event. Cloud cover or vapor trails can also hide portions of an event.

Flight test and evaluation projects typically encompass factors unique to that project. The photogrammetric solution methodology must incorporate the flexibility to accommodate an expanding range of project requirements. An example of a recently completed project is the Advanced Medium Range Air-to-Air Missile (AMRAAM). The purpose of the AMRAAM project was to establish and recommend ejected launch and jettison release envelopes for the AMRAAM on F/A-18C/D aircraft. Since the AMRAAM is a long slender store, part of the challenge for the project was in designing a targeting scheme to optimize tracking of the missile.

4. THE AIRBORNE PHOTOGRAMMETRIC PROCESS

The primary objectives of the NAWCAD airborne photogrammetric process are:

- to obtain data from surveys of the aircraft or store
- to create the optimal camera configuration to capture the event
- to accurately and rapidly reduce and convert readable event data
- and to provide an analysis report to the customer.

4.1. Photogrammetric Targets

Typically 20 or more targets are placed in a predetermined pattern on the store to allow for more accurate photogrammetric analysis of the position of the stores. For cameras prone to in-flight movement (ex. the aircraft wingtip), over 100 targets are painted or affixed to the aircraft to correct the camera position. Of special interest to the photogrammetric team is the design and placement of the targets attached to or painted on the aircraft and store. The shape, color, and location of the target are critical to the accuracy of the photogrammetric solution. If the target is clearly identifiable on film or video, the photogrammetric team can produce accurate answers. A poorly designed target will hamper the photogrammetric process and can diminish the integrity of the photogrammetric solution. Extensive flight testing has proven that as the number of targets (tracking points) on the store are increased the accuracy of the solution is increased; however, the number of targets is limited for practical reasons based on the time to install, survey, and analyze the increased number of targets. The typical target sticker used is a 4 or 6 inch square with a bow-tie or bulls–eye feature. More recently a sticker material was discovered that remains attached to the store and aircraft over the entire flight envelope (including supersonic) and adverse surface roughness. The most effective color combination is black and white.

4.2. Camera Configuration and Orientation

Photosonic 1PL high-speed 16mm film cameras running at 200 frames-per-second are externally mounted to the aircraft to record store motions during release. IRIG time is routed to each camera from the onboard aircraft instrumentation system and printed between the sprocket holes of each frame. As a result of the multi–camera photogrammetric solution requirement, Photosonic designed a phase–lock unit driven by IRIG time to allow each camera to simultaneously take pictures. The cameras are oriented to maximize overlapping fields of view. Because some stores start as close as 4 feet from the camera and the measurement

volumes are very large, 5.9mm and 10mm lenses are typically used. As a result, optical distortion must be calculated and corrected. A lens calibration picture is taken with each camera/lens combination of a spiked calibration board with 140 targets and 12 spikes serving as the orientation guide. Until recently, optical distortion was assumed to be radial. During planning for a particular project, there was a requirement to place a camera behind a cylindrically curved window. Consequently, a non-radial distortion algorithm was developed and is currently used for all distortion corrections.

4.3. Aircraft and Store Photogrammetric Survey

Photogrammetric solution algorithms rely on surveys of aircraft and stores. It is imperative that these measurements be accurate. Survey requirements include:

- Aircraft and store target positions with respect to the aircraft and store coordinate systems respectively
- Positions of each camera's focal plane with regard to the aircraft coordinate system
- Measurements accurate to within 5mm for aircraft targets and 2mm for store targets.

Because survey tools and methods vary and because of unique photogrammetric-oriented survey requirements, the NAWCAD Photogrammetric Team employs its own survey tools, methods, and experts. Due to the large size of the aircraft, the NET-2 laser transit is used to survey photogrammetric targets affixed to the aircraft. A typical aircraft survey takes three days. Although the NET-2 has been used for store surveys, the instrument used for most surveys is the FARO arm. By standardizing the tools and processes for aircraft and store surveys, the potential for erroneous, incompatible, or incomplete survey measurements is significantly reduced. Accurate and complete photogrammetric survey measurements provide an increased range of options when problems are encountered during a photogrammetric event or analysis.

4.4. Film and Video Data Reduction

Sixteen millimeter film media is used for weapon separation tests, 35mm film is used for carrier suitability tests, and 35mm film or video is used for ballistic trajectory and overhead scoring tests. Image data are reduced using two processes: Telereadex Film Reading Machines are used for reading 16mm and 35mm film and the Semi-Automatic Film and Video Reader (SAFVR) is used for 16mm film, 35mm film, and video data. For a typical stores separation flight, eight cameras with 100 frames of useable data with an average of 12 photogrammetric targets visible on the store result in approximately 9600 data points per flight.

The Telereadex Film Reading Machine is a 30–year–old manual film digitizer recently refurbished by Loel Systems Integration to incorporate a PC-based interface. The film is fast forwarded to the first frame of the first event to be read. Film reading experts align horizontal and vertical (u,v) cross hairs on specified photogrammetric targets on the object to be analyzed. This manual process is repeated for each photogrammetric target in the image and for each image in the film sequence.

The SAFVR is a system developed by Amerinex Applied Imaging specifically for photogrammetric data reduction at NAWCAD. The SAFVR digitizes 16mm and 35mm film using an Oxberry Film Transport and a Kodak 1.6 Megaplus 10 bit camera compressed to 8 bit. The SAFVR is a Sun workstation-based system with a graphical user interface (GUI) that allows the operator to digitize film at three frames-per-second. Videotapes from various formats can also be digitized into the system. To track a photogrammetric target within an image sequence, the SAFVR may:

- Allow manual tracking of a target by an operator
- Select one or more targets for automatic tracking of manually identified targets
- Use the survey data to allow the SAFVR to automatically track features

Photogrammetric targets can be tracked by the SAFVR by using feature-based, centroid-based, and correlation-based tracking algorithms.

Since a stores release flight must be conducted at specific release conditions, adverse lighting and atmospheric conditions, such as water vapor, can obscure a photogrammetric target from the view of a camera. As the store is released, it may emerge from a strong shadow under the wing to full sunlight. Lighting conditions at high noon are much different than early morning or late afternoon. In addition to environmental problems, the aircraft flight test loadings may obscure the store during part of the release. For example, releasing a store from an outboard wing station with a fuel tank on the inboard wing station will partially obscure the cameras mounted on the fuselage of the aircraft.

4.5. Photogrammetric Database

As a result of a large increase in survey, camera, mass property, and film/video data, an Informix–based relational database was developed to provide operational management of the entire process. In addition to the large volume of data, mass property measurement, store survey measurement, camera maintenance, and film and video reader functions are not collocated. Use of the

photogrammetric database and well defined processes allow for data to be gathered without direct supervision by the photogrammetric team leader. The remote sites send data via file transfer protocol (ftp) directly to the Informix database which resides on a Sun-based, fiber optic network using a 200 gigabyte Alphatronix optical media jukebox as the mass storage device.

5. PHOTOGRAMMETRIC ANALYSIS

To obtain accurate time space position information of a store, several camera solution techniques are applied including a single camera solution and a multicamera triangulation solution. Each solution technique has inherent advantages and drawbacks.

5.1. Multi-Camera Triangulation

The primary photogrammetric solution technique is the multi-camera solution. Since the physical and environmental conditions inherent to the flight testing environment can result in poor image quality for film and video data, it is imperative that the photogrammetric solution algorithm incorporate techniques that can be adapted to a variety of conditions. Multicamera solutions increase the probability of getting valid answers throughout a range of test conditions, including:

- camera malfunctions
- poor quality film
- additional stores other than the subject of the stores separation event being attached to the aircraft, such as a fuel tank
- inaccurate survey of aircraft and/or store.

The NAWCAD multicamera solution configuration requires data from at least two cameras to produce accurate solutions. The NAWCAD multicamera solution methodology does not require cameras to be grouped as pairs, rather, data from each camera are approached as a separate entity. If data are missing from a particular camera, there is no corresponding degradation or "simplifying assumption" that affects the data from another camera. With multicamera solutions, each additional valid data source represents a corresponding increase in data accuracy that can not be attained via single-camera solutions. However, the loss of any one source or multiple sources does not degrade the data from the remaining source(s). Because air-launched stores are typically long and slender, accurate measurement of roll can be a problem; however, the multicamera solution process generates accurate roll data because the store is viewed from multiple camera angles. The data afforded by a multicamera solution drastically reduces the role of "operator judgement" inherent to a single camera solution. One of the primary advantages of the multicamera solution methodology is that multiple camera angles and multiple tracking points provide the data sources necessary to detect and eliminate depth perception errors that plague single camera solution configurations.

For the multicamera triangulation algorithm, three or more cameras are used to quantify error. Four or more cameras can be used to determine relative error (i.e. identify which camera can be rejected — such as a camera with a bad calibration).

5.2. Single Camera Solution

During a stores separation flight test, a variety of factors or combination of factors such as camera malfunction, cloud cover, or vapor trails can eliminate data from one or more cameras. Occasionally, valid data can only be obtained from one camera. Under these circumstances, a single camera solution is implemented. Single camera analyses have resulted in solutions that are:

- unstable (has more than one point of convergence)
- prone to drift (mathematically weak in convergence)
- not redundant (hinders troubleshooting problems).

A major advantage of a single camera solution is the reduced man hours for film reading and camera setup; however, viewing an event from one camera angle results in heavy reliance on operator judgement.

5.3. Product Presentation

A final photogrammetric trajectory solution is presented to the customer usually in one of two ways: Tabular data or graphical outputs. Tabular data are electronically delivered to the customer or plotted. The graphical plot is a pictorial three-view representation of the photogrammetric analysis as shown in Figure 2.

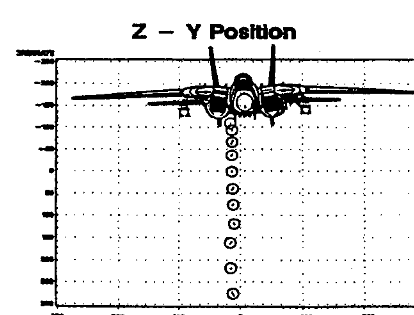

Figure 2. Graphical plot of photogrammetric data

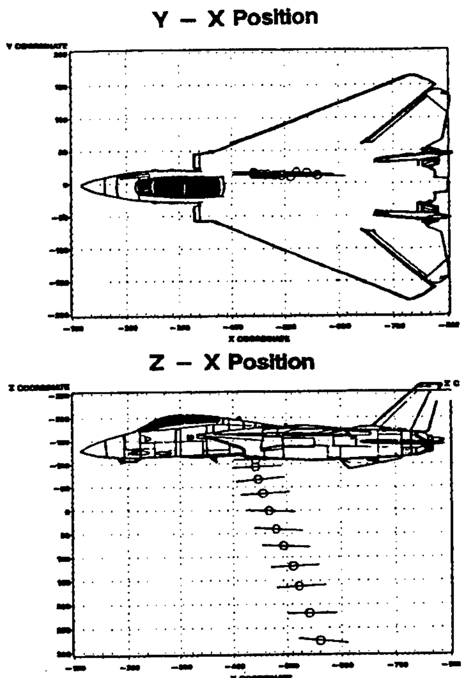

Figure 2 (con't). Graphical plot of photogrammetric data

6. QUALITATIVE ANALYSIS

In addition to the analysis techniques previously described, the SAFVR was also designed to allow for qualitative analysis of film data. The Megaplus camera coupled with the Oxberry film transport can be zoomed to within one-quarter of a 16mm frame and panned about the frame at the full resolution of the Megaplus camera. This allows enhancement of features or events during the test which are not associated with photogrammetric analysis. For example, arming wires approximately 3/32 inches in diameter are used to activate high drag devices on the store during release. If the device should fail to activate, close examination of the film is required to determine the probable cause and to propose corrective action. To assist in the qualitative review, analysts employ image enhancement algorithms such as:

- edge enhancement
- smoothing filtering
- contrast manipulation
- pseudo-coloring
- image differencing
- histogram equalization

Finally, the digital images can be compiled in a movie for distribution to the customers. Movies are distributed to the customer on video tape or in standard image compression formats.

An alternative presentation technique is to animate the photogrammetric solution from the perspective of the camera view to allow qualitative comparison of the original film data. The original film view can be displayed picture-in-a-picture to facilitate comparison. Animation has also been used as a pre-test tool to evaluate camera field of view of an upcoming test for photogrammetric analysis.

7. CONCLUSION

In 1991, the U.S. Navy committed to upgrading the F/A-18 aircraft as the most cost-effective and efficient means to meet the need for a 21st century strike fighter aircraft. Success of this program mandates quick and cost-effective flight test analysis during development of the aircraft. To meet these requirements, the NAWCAD Photogrammetric Team launched a major review and upgrade of the existing photogrammetric process. Based on the smooth progress of the F/A-18 E/F flight test program, NAWCAD has demonstrated the operational application of photogrammetric analysis in a high tempo, high volume, technically adverse environment, which will result in cost-effective flight test services for the United States Navy.

ALENIA APPROACH TO THE AERODYNAMIC INTEGRATION OF EXTERNAL STORES ON AIRCRAFT

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SUMMARY
The analysis of the store separation trajectories, finalised to the definition of safe release envelope, is one of the most important task to overcame in the aerodynamic design area for the integration of external stores on a combat aircraft.
With this paper Alenia presents the methodologies used in this activity outlining the recent progress obtained with the availability of new advanced tools (Hardware and Software) in the field of CAD and digital image processing.

1. INTRODUCTION

The integration of external stores on military aircraft is one of the most important task to overcome during an air vehicle design.
Within this task the analysis of the store separation behaviour, finalised to the verification of jettison safety, has a fundamental role having the objective to define the operational release envelopes.

This paper d. ·:ribes the methodologies and the process used by Alenia to assess the store separation behaviour and to define the safe release envelope.
A particular emphasis will be given to the new advanced tools (Hardware and Software) adopted in the store integration process in order to improve the reliability and to get a better integration between prediction and post-flight analysis phases. The CAD methodology (CATIA) is now deeply used to handle store/aircraft geometry in support to grid generation, to optimise the field of view of the camera installed on aircraft and as a post processor to get an accurate evaluation of the minimum store distances from the parent aircraft. Moreover the advent of new technologies li.e digital image processing and solid-state TV cameras has allowed, in the last few years, to strengthen significantly the effectiveness and the applicability of image-based flight test analysis. In particular an advanced system for digitising and automatically analysing film and TV images was purchased by Alenia Flight Test and it is extensively used in the store separation analysis making more effective the analysis and in developing new flight test techniques based on optical inputs. Initial successful results were obtained in' solving different peculiar analysis problems, in particular weapon aiming measurement and safe separation.

In the following part of the paper a brief synthesis of the results of the integration of a new generation of bomb on a combat aircraft will be presented as an example of the application of the above mentioned methodologies.

The activity for the integration of a generic external stores on aircraft is carried out in three different phases:

- Pre-flight analysis is based on the application of the mathematical model with the object to define the initial safe release envelope for flight tests.
- Flight trials are carried out through a fly-match-fly process with the aim to acquire experimental results useful for the mathematical model validation.
- Post-flight analysis is based on the application of the validated mathematical model with the aim to investigate the store separation behaviour within the whole required release envelope defining the final clearances.

2. PRE-FLIGHT ANALYSIS

The pre-flight analysis consists in the evaluation of the store behaviour through the application of a mathematical model solving the six degrees of freedom equations of motion.
The model is used to predict the store separation trajectories and is applied to investigate the whole required envelope covering all the different aircraft configurations.
The pre-flight analysis has two main objectives. The first one is to provide a preliminary indication on the store separation behaviour in order to identify possible areas of potential criticality. In such a way it will be possible to intervene during the initial design phase introducing the suitable modification to improve the store separation.
The second one is to define an initial safe flight envelope within which to start the experimental jettison demonstration providing the store separation predictions for the selected test cases.

The standard method currently used by ALN is named Store Separation Trajectory Program (SSTP). This technique has the advantages to use a fixed aerodynamic data set (aircraft flow field, store free-air coefficients and installed loads), making its application very fast and cheap. The comparison with the results of a lot of flight test cases has proved its reliability for most of stores and release conditions investigated.

Nevertheless for those cases where the flow regimes are characterised by non-linear phenomena and when

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

the store trajectory could be potentially critical a more accurate method is applied. This new technique called APRICOTES (**A**lenia **PR**ocedure for **I**nterference **CO**mputation on **T**rajectories, **E**uler **S**upported) [1] is based on the application of 3D Euler code to evaluated and update the airloads on the separating store at different steps along its initial part of trajectory.

The fig. 1 shows the complete flow diagram of the activities to be performed to achieve the final operational clearance as far as the store safe separation is concerned.
As shown in the above mentioned flow diagram the store trajectory calculation is influenced by the following parameters:

- Aircraft flight conditions
- Store mass and inertia characteristics
- Store aerodynamic coefficients (Free-air)
- Aircraft/store aerodynamic interference (Installed loads)
- Aircraft flow field
- Ejector Release Unit (ERU) performance
- Motor thrust characteristics for propelled store
- Store physical constrains (Rail hanger, hook)
- Parachute characteristics (Drag) for retarded stores

Among all the above mentioned parameters, making up the mathematical model data set, the aerodynamic data are those having the most influence on the store separation behaviour and demanding the major effort for their determination.

A brief description of the techniques and methodologies adopted to generate the aerodynamic data set is given in the following.

2.1 Store free-air coefficients
The free-air aerodynamic coefficients are generally provided by the store supplier with dedicated wind tunnel testing.
To take into account of the effect of the variations of the flow field, within which the store is submerged, the global coefficients are split in several sections. The partition of the global coefficients is made proportionally with the equivalent values obtained, for each respective section, through the application of Euler 3D codes, in this way the reliability of the experimental data is kept.

2.2 Store installed loads
The installed loads give the aerodynamic coefficients of the store in its carriage position taking into account the mutual interference between store and aircraft. The accuracy level of these data has a fundamental importance in the store separation prediction work since they are the basis for the determination of the aerodynamic forces and moments acting on the store at the release instant.
The initial value of the installed loads are decaying linearly to zero at a distance (normally 2 -3 times the store diameter) for which the effects due to the mutual interference phenomena between store and aircraft are considered negligible.
The aerodynamic loads on a store when installed on the aircraft are often characterised by non-linear phenomena due to heavily disturbed flow field generated at transonic speed conditions combined with complex configuration geometry's.

For this reason the installed loads are generally derived by wind tunnel testing. The 3D Euler code is used many times jointly with wind tunnel data to cover those external store configurations or flight conditions for which the experimental data are missing.

2.3 Aircraft Flow Field
The store during its initial separation crosses a region of highly perturbed flow, mainly due to the presence of the parent aircraft.
The flow field characteristics defined in terms of local incidence ($_l$ and $_l$), Mach number (M_l) and dynamic pressure (q_l). are determined for the clean aircraft configuration covering the whole ranges of speed, angle of attack and sideslip of the required release envelope.
The acquisition of these data is generally made theoretically through application of CFD codes. (Panel Method or Euler 3D).

2.4 The ALN approach to the application of CFD code into the aero-design process.
To support the application of CFD codes in the aero-design process ALN have developed a procedure, based on the integration between CAD-CATIA system and CFD codes; which, starting from an initial geometry, leads to the analysis of CFD results.
This sequence of operation allows to get quick and reliable process of aero-design: an example of the steps of the process is presented in the fig. 2 and described in the following:

- Definition of a "conceptual" model (for instance as first step of a development of new configuration or utilisation of a model from the master geometry data base (already assessed geometry).

- Building up in CAD-CATIA contest of a derived geometry model (by "translating" a series of points in polynomial entities) congruent to that defined in the previous step. This step allows reducing the amount of geometrical information to be managed and to verify the possible deviations of the derived geometry with respect to the original one.

- Possible simplification of the geometry depending on the aircraft area to be analysed.

- Transfer of the geometrical data (polynomial coefficients) from CATIA to the input files of CFD codes with the appropriate format.

ALN have developed a 3D Euler flow solver named UES3D, ref. [2]. The aim of the code is to find the flow field stationary solution of a three dimensional compressible inviscid fluid by using a pseudo-unstationary method in time and spatial finite volume method on unstructured tethraedical meshes, ref. [3].
During the application of 3D Euler code the following steps are performed:

1. Generation of surface and spatial grids to produce the flow field discretization to be used by the analysis code.

2. Numerical results from Euler equation solutions (UES 3D code) and analysis of these results.

3. Optimisation of the model on the basis of the result analysis and consequent verification with numerical code.

4. Final assessment and loading of the new model in the master geometry database.

The implemented methodology, having access to a direct way to the mathematical models of the assessed geometry, permits to carry out aero-analysis with strongly representative models.

The application of this methodology allows to quickly and correctly optimise the geometrical model utilised for the aero-analysis.

The optimised geometry can be easily re-inputted in the master geometry database.

The above described methodology represents the standard procedure of the whole aero-design process. It can be usefully used even in the trajectory calculation limiting the application to an aero-analysis contest.

2.5 Pre-flight analysis results.

In this part of the paper a brief synthesis of the results of the pre-flight analysis carried out for the integration of an advanced guided bomb from a combat aircraft are presented as an example of the application of the methodologies described previously.

The bomb is built mounting on the body of a general purpose bomb a kit composed of a forward guidance control unit and a rearward airfoil group.
This is a very complex configuration from an aerodynamic point of view being characterised by the presence on the nose of a partially free-floating canards producing an unstabilising contribution and by a tail with moving wings, which opening occurs progressively during the bomb separation.

To calculate the separation trajectory of the bomb a complete aerodynamic data set has been prepared.
The free-air aerodynamic input data are composed by three set of coefficients relevant to three different bomb configurations:

- Folded tail wings
- Intermediate tail opening
- Full deployed tail wings

The correct value of the coefficients in each instant of the bomb separation trajectory are obtained interpolating the aerodynamic data set versus the time history of the tail opening law,
The bomb separation trajectories are computed through the application of the mathematical model: Store Separation Trajectory Programme (SSTP) mentioned in previous paras.
During the investigation the whole required envelope has been explored taking ,into account of tolerances and possible failure having a negative impact on the bomb separation safety.
The results of this analysis has assessed that to have a safe separation of the bomb in the full release envelope an ejector release unit partialization, giving an initial pitch down, is necessary in the case that a missopening of the bomb tail wing occurs.

The fig. 3 shows, for one significant condition, the comparison between the trajectories obtained with the two ERU solutions (with and without pitch control) evidencing the significant improvement obtained on the bomb separation.
As conclusion of the investigation an initial safe release envelope has been defined within which it was possible to flight and release the bomb.
In addition two significant flight conditions useful to validate the mathematical model have been identified to be tested in flight.

3. FLIGHT TRIALS

The flight release trials are essential part of the store integration process on aircraft. The main purposes of the flight test are to demonstrate the safe separation, to provide experimental results for mathematical model validation, and to prove the correct functioning of the release systems and of the store dressing.

The whole process, which leads to the film availability for the analysis, consists of several steps, such as store dressing and markering and cinecamera position optimisation and harmonisation.
In the following paragraphs, an analysis case carried out on a bomb type is presented, in order to clarify with a "true case" the test preparation, film analysis and trajectory calculation phases.

A proper markering scheme (see Fig. 4) has been defined and applied to the stores used for the release tests, in order to use at its best the automatic tracking system capabilities (Trackeye), gathering precise and smooth 2D co-ordinated for the 3D trajectory calculation.
The definition of the flight test conditions was based on the results of the theoretical pre-flight analysis, which "predicts" the store behaviour in flight.

The on-board camera films are the main source of information for the store trajectory calculation; the cameras were properly fitted on board (see Fig. 5); each camera used during the trials was before characterised by its lens distortion values, used by the analysis S/W for the distortion correction. It has to be pointed out that this data were gathered taking also into account the characteristics of the Trackeye system, from which the films are digitised and analysed.
Armament basic data were recorded to allow the correct correlation between the cinecameras and the precise identification of the weapon release time on the film frames; in particular, the pilot Weapon Release Button was used to activate an event light and marking in this way the film on one side. Markers were recorded at predefined time interval on the other side of the film, used during the quick-look analysis and the further film data reduction phase.

After the flight, the relevant films were analysed, gathering store position and attitude for each frame, obtaining the experimental trajectory to be compared with the theoretical prediction.

3.1 Flight Analysis Tools

The manual analysis process for 2D co-ordinates gathering from films which has been used by Alenia for a long time proved to be a time consuming and demanding task since very numerous films, pertaining

to different viewpoints, have to be examined for each store.
For these reasons, in 1988, a research was undertaken aimed at deepening the problem of automatic images analysis with the purpose to render the process quicker and possibly more consistent.

Main specific requirements for the System were:
- Capability to accept both TV and film (16mm) inputs;
- no need of luminescent, coloured or retroreflective "markers";
- very limited operator intervention required;
- high accuracy (not less than that achievable by means of present manual process);
- affordable cost.

After largely circulating a request for proposal, the conclusion was reached in favour of the system named TrackEye. That was considered in fact the best compromise between cost and performance.

Since 1991, Trackeye system is used in ALN store trajectory calculation process (see Fig. 6): the system provides bi-dimensional co-ordinates of selected points on the store with respect to a reference frame. The output data are then analysed by a dedicated S/W programme which determines the 'information on depth' (z co-ordinate) and the attitude angles, considering the optical cinecamera characteristics and the lens distortion.

3.2 System overview
Trackeye (Fig. 7) is a complete system for automatically measuring the movements of various objects in a sequence of images from video or film.
It covers the whole process from images digitising up to analysis and results presentation.
The inputs of the system are recorded sequences on, either video or film, and the outputs are diagrams and co-ordinate data of selected points, not necessarily marked, of the tracked object.

TrackEye Motion Analysis System consists of a basic software package aimed at the purpose of standard motion analysis of picture sequences. The system provides three main functions: Recording, Tracking and Analysis.
Recording function allows digitising and storing a sequence of images generating a Video Disc Image File.

The Tracking menu contains Functions for overview of an image sequence stored in the system, the definition of a sub-sequence for tracking and selection of several modes of tracking; in this phase one can define points and track them automatically or through operator control. In fact the working mode (fully automatic, semi-automatic or manual tracking) can be chosen by the Operator.
In the fully automatic mode the computer tracks the marked objects without any operator's intervention.
In semi-automatic analysis the system suggests a new position for each new frame, but requires the operator to correct or accept it before proceeding.
It is easy to add new points of interest and also to remove (make "sleep") points that temporarily or permanently vanish.
The system stores the point co-ordinates that can be subsequently picked up for further processing.

Immediately after tracking, in the Analysis phase, TrackEye can evaluate and present a set of different parameters, including position, distance, linear and angular speed and acceleration of the previously selected points.
Various transformations and calculations (i.e. interpolation, smoothing etc.) may be performed, the results of which can be displayed in diagrams having different shape and size; the original images sequence can also be visualised with superimposed points tracked path.
As final results, diagrams and images of the above mentioned information can be printed (see fig. 8) and the file containing the points of the 2D co-ordinates can be exported for the subsequent 3D analysis.

3.3 Analysis process and validation
The data analysis process data flow is described in the diagram flow already shown in Fig. 6.
The 2D co-ordinates derived by the films together with the store reference data, camera constants and lens distortion correction are the inputs for the 3D photogrammetry analysis which, solving the collinearity equations, derives a 3D motion estimation.
The results of the trajectory reduction programme consist of the X, Y and Z store positions in A/C axes, as well as pitch, roll and yaw angles and rates.
Output are provided for the post-flight analysis phase in different formats like plots and files.

It has to be pointed out that the availability of a modern and flexible tool for image processing revealed to be effective for speeding up and making more consistent the process.
However, before undertaking a systematic use of the new tool for actual analysis, flight test engineers wondered how the reliability of the results could be proved.
To the purpose a dedicated test rig was developed, based on the use of a representative mock-up of a store, capable of reproducing on ground, in true size, a six degrees of freedom movement during a simulating release. In this way, a "reference" phenomenon is made available, without limitations, every time it is necessary.
It also allows to gather, for a set of pre-defined store position, "quasi-perfect" reference data about its actual 3D dynamic, to be used for assessing the error related to the new automatic process.
The dummy bomb, conveniently painted is hung up by four supporting arms of different length (adjustable) in order to generate, while oscillating, pitch and yaw movements. The bomb can roll around its simmetry axis too.
A system flexibility test in a dynamic phase has been also carried out before the beginning of the testing; the main purpose of this test was that of defining the influence of the inertial and plays effects on the movement repeatability. To do that, some dot light sources have been placed on the dummy-bomb, which was forced to undergo swinging in the dark, both continuously and step by step.
Observing the obtained images it was verified that the above mentioned effects are definitely negligible.
A number of simulated releases have then been performed, in different conditions, recorded by cine and video cameras and analysed. The comparison with the absolute reference data has given the engineers the required confidence about the quality of the process.

4. POST-FLIGHT ANALYSIS

The main objective of the post-flight analysis is to match and validate the mathematical model used during the pre-flight analysis on the basis of the experimental results in order to obtain a reliable tool to be applied for the final assessment on the store separation safety.

The comparison between the trajectory derived by the film analysis and the predicted one allows to verify the accuracy of the input data and the validity of the assumptions made into the initial mathematical model and when necessary to introduce the suitable changes. Referring to the examined cases the figs 9 and 10 shown a general good agreement between experimental and predicted bomb trajectory.

An important improvement in the store separation analysis has been obtained by the use of CAD-CATIA system which allows to represent with high accuracy the detail geometry of the store trajectory and the aircraft configuration. Moreover, in case of store having moving surfaces, the CAD-CATIA allows the representation step by step of the actual store geometry.

The geometric model, so obtained, allows to analyse in detail, with opportune image rotation and zooming, any part of the released store presenting possible risk of collision with the parent aircraft or with other adjacent stores. In addition an accurate assessment of the minimum distances of several selected points of the store is also achievable in automatic way.

On the bases of this results the SSTP mathematical model can be considered fully validated for the subsequent investigation of the bomb separation in the whole required release envelope.

The expected final result of the investigation consists in the definition of the safe flight release envelope providing the evidences for the issue of the operational clearances.

5. CONCLUSIONS

The results of the presentation have shown as the adoption of new tools (CAD and Trackeye) have introduced significant improvements to store separation analysis process.

The availability of the Trackeye system has given to the flight test engineers an effective tool for the image analysis making quasi-automatic the film reduction process.

The digital image process has the advantage to make the store trajectory analysis quicker and more reliable due to the less incidence of human errors.

The application of CAD-CATIA in the aero-design contest allows to quickly and correctly optimise the geometrical model for the subsequent CFD analysis.

Other important application of the CAD is its use as post processor in separation trajectory analysis; in fact the detail geometric model of the aircraft and store allows the estimation of the relevant minimum distances with the maximum accuracy level.

Reference

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[2] SELMIN V.; HETTENA E.; FORMAGGIA L.:
"An unstructured Node Centred Scheme for the Simulation of 3-D Inviscid Flows" In Proceeding of the First European Computational Fluid Dynamic Conference (1992).

[3] FORMAGGIA L.:
"An Unstructured Mesh Generation Algorithm for Three Dimensional Aeronautical Configurations" in Numerical Grid Generation in Computational Fluid Dynamics and Related Fields, A. S. Arcilla et Al. Eds., Elsevier Science Publishers B. V. (North-Holland) pp. 249-260 (1991)

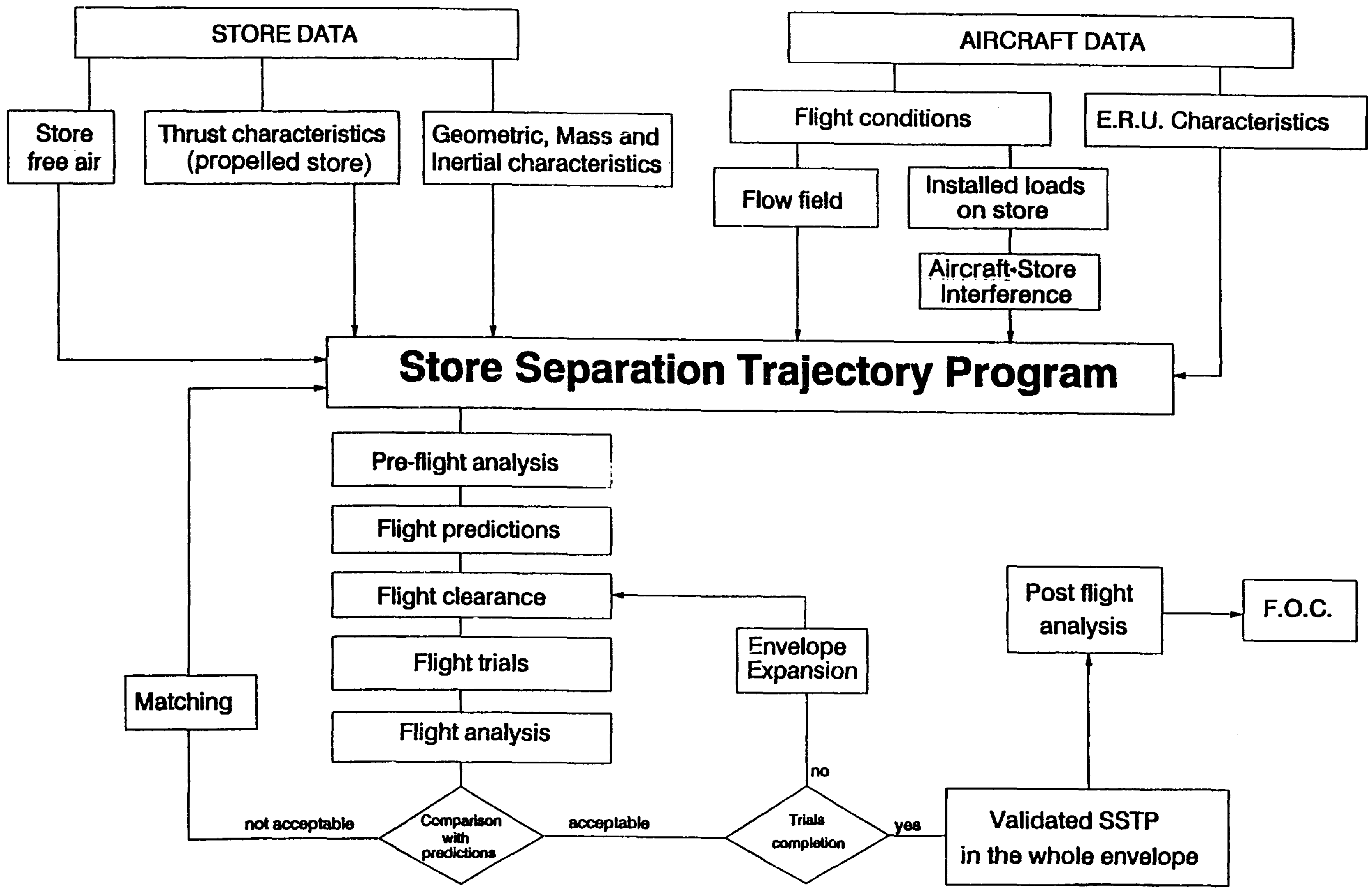


Fig. 1 FLOW DIAGRAM OF STORE INTEGRATION ACTIVITY (SAFE SEPARATION ASPECTS)

Fig. 2 CATIA-CFD INTERFACE IN AERO DESIGN PROCESS

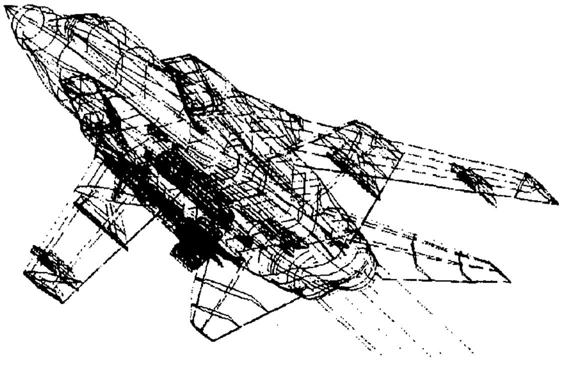


Fig. 2a ORIGINAL GEOMETRY (CATIA SURFACES)

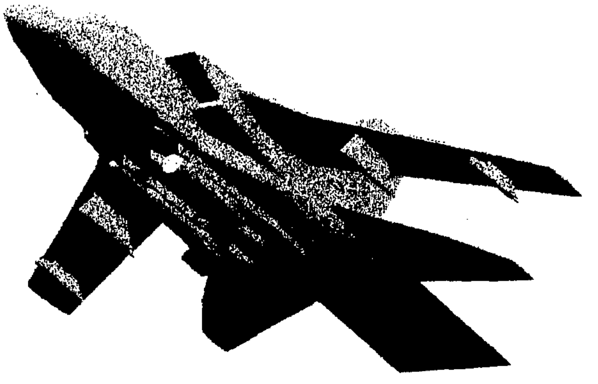


Fig. 2b SOLID MODEL (CATIA CONTEST)

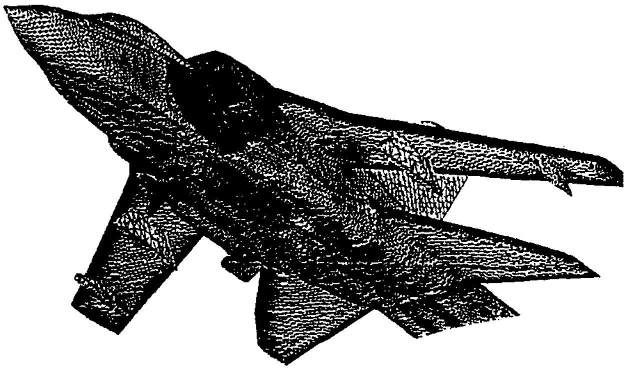


Fig. 2c SURFACE GRID (SUR 3D CODE)

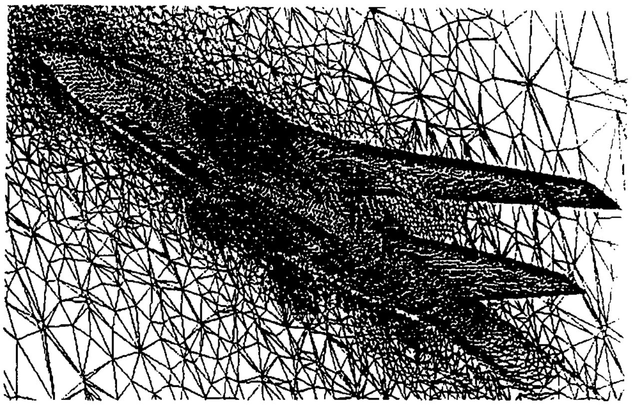


Fig. 2d SPATIAL GRID (M3D CODE)

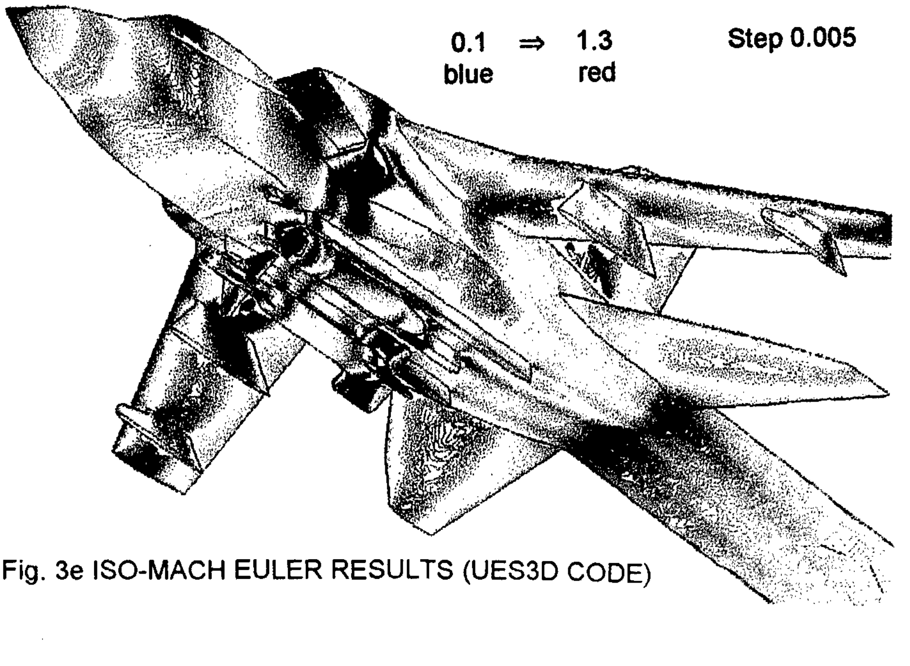
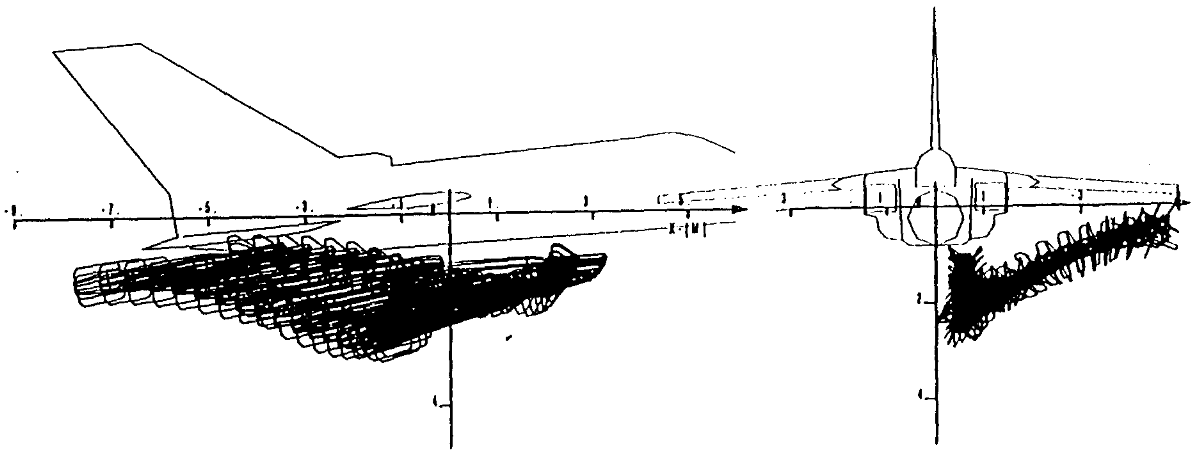
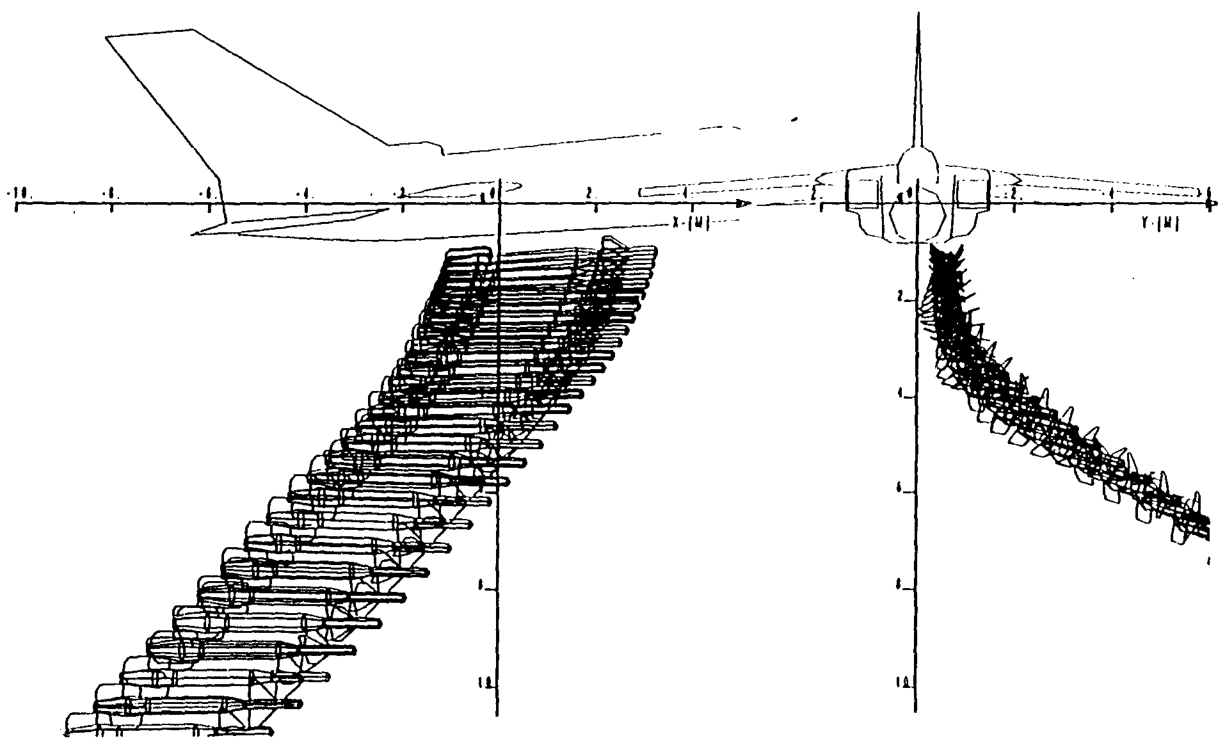


Fig. 3e ISO-MACH EULER RESULTS (UES3D CODE)

Fig. 3 PITCH CONTROL EFFECTS ON BOMB SEPARATION TRAJECTORY

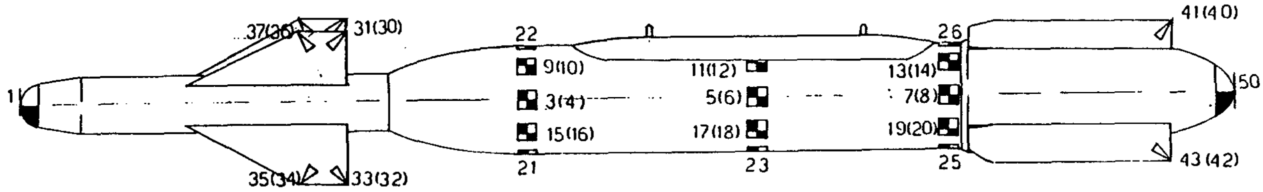


WITHOUT PITCH CONTROL



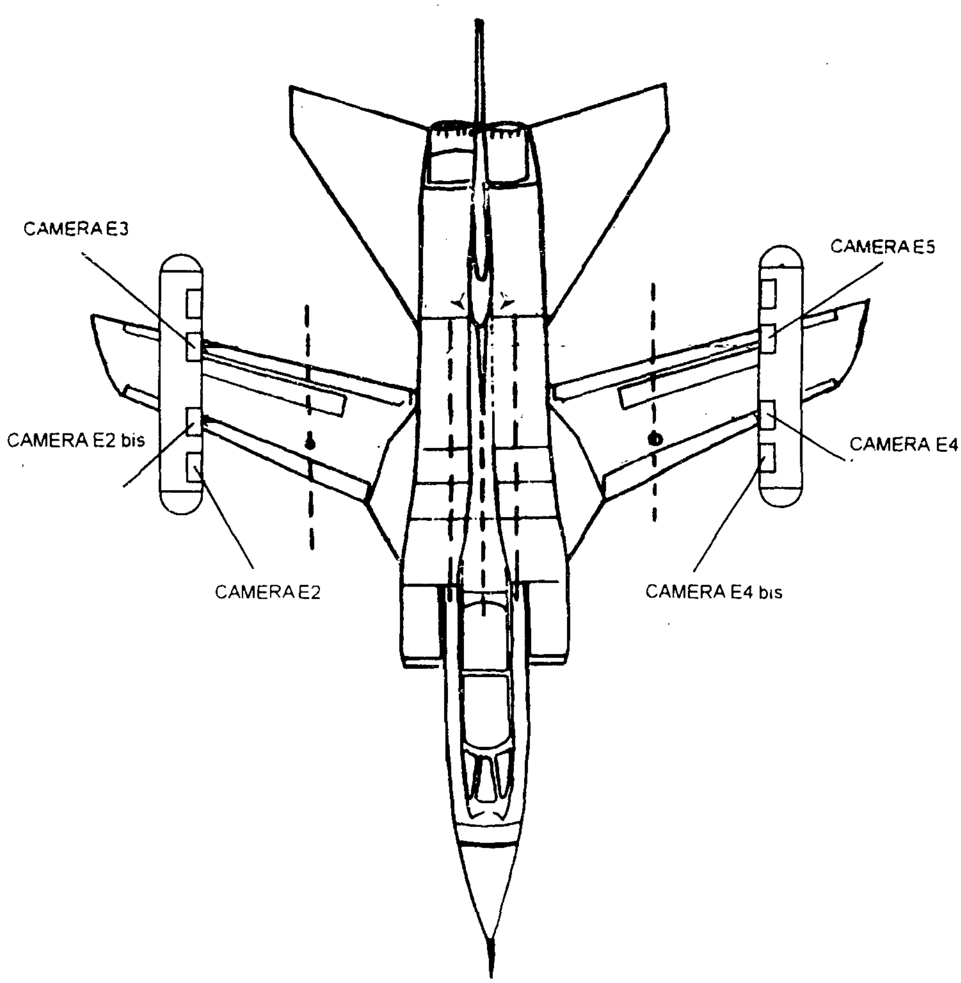
WITH PITCH CONTROL

Fig. 4 SCHEME OF BOMB MARKER CHARACTERIZATION



NUMBERS IN BRACKETS → OPPOSITE SIDE
ARROW SYMBOL SHOULD BE PAINTED ON BOTH SIDES OF EACH WING AND FIN

Fig. 5 SCHEME OF ON-BOARD CAMERA INSTALLATION



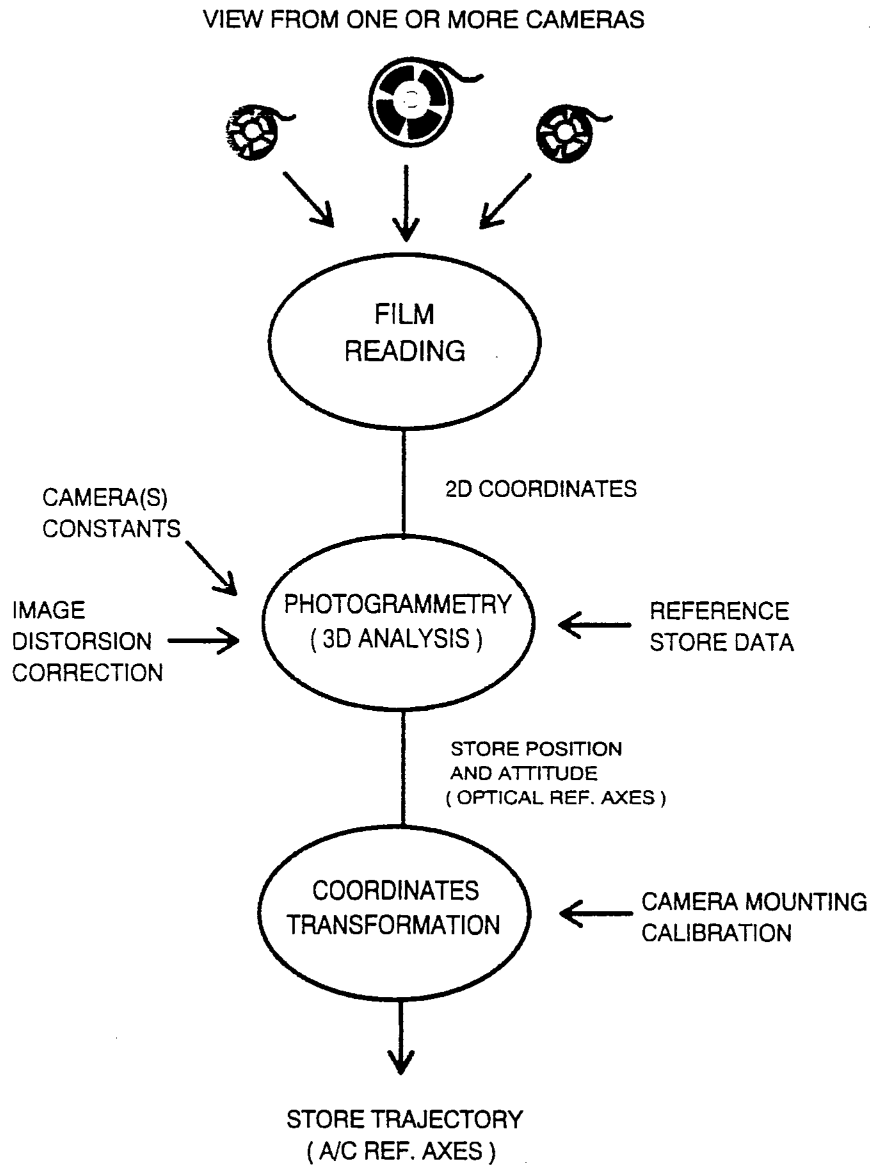
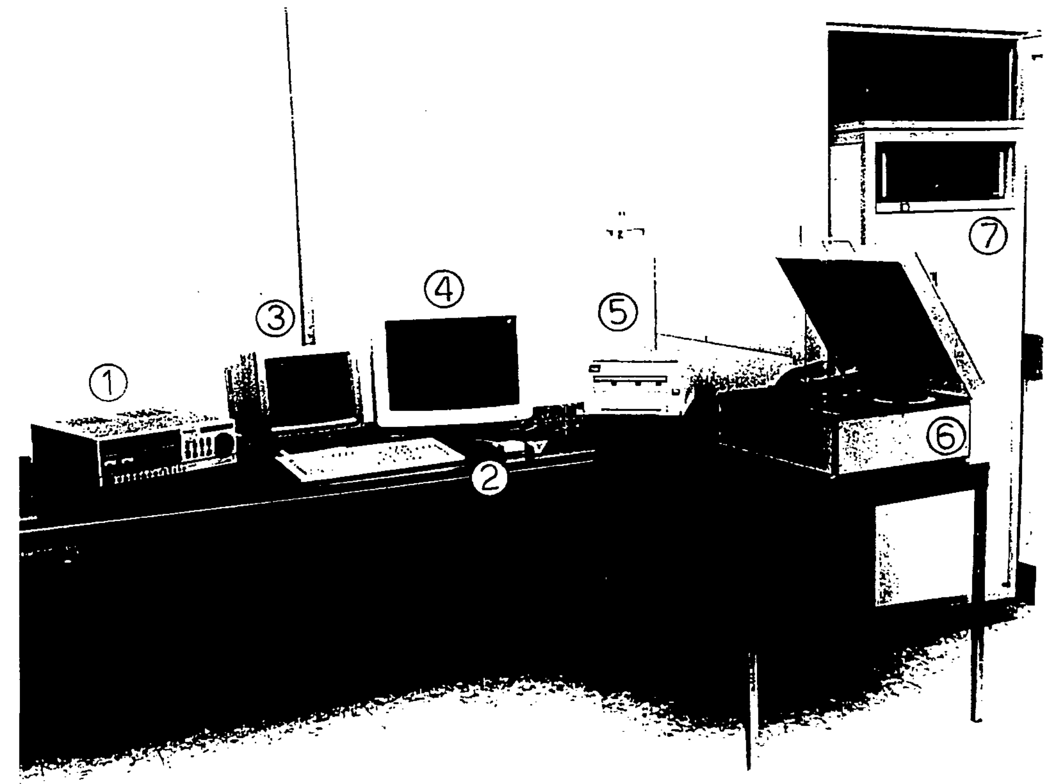


Fig. 6 TRACHEYE ANALYSIS PROCESS FLOW



1) Video Tape Recorder
2) Keyboard / Mouse
3) Host Computer Monitor
4) Color Display Screen
5) Laser Printer
6) 16 mm Film Scanner
7) Image Processor

Fig. 7 TRACKEYE IMAGE WORK STATION

Fig. 8 OUTPUTS OF TRACKEYE ANALYSIS RESULTS

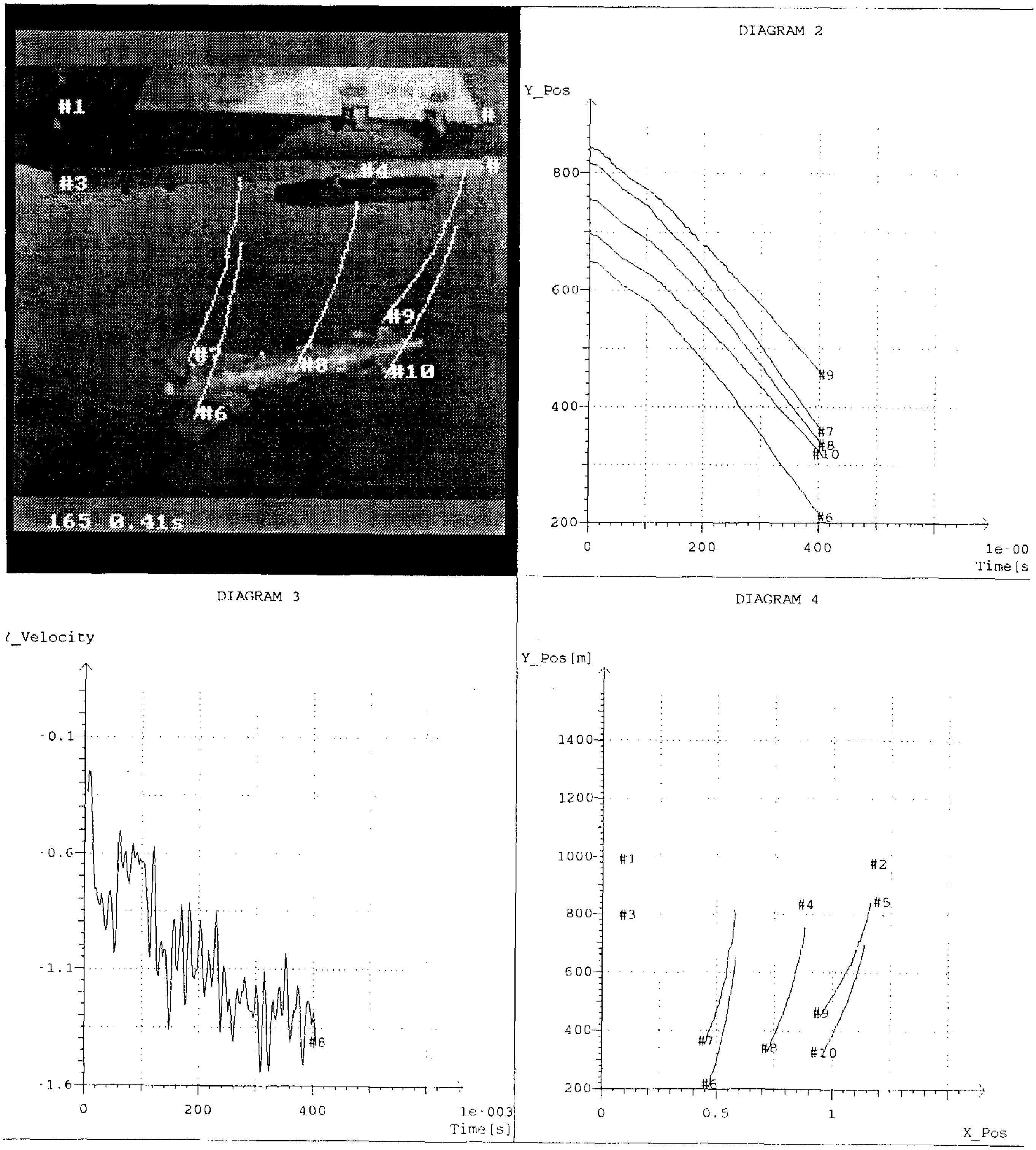
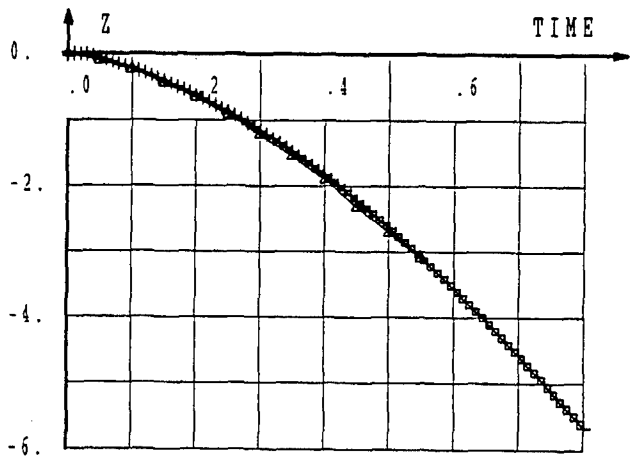
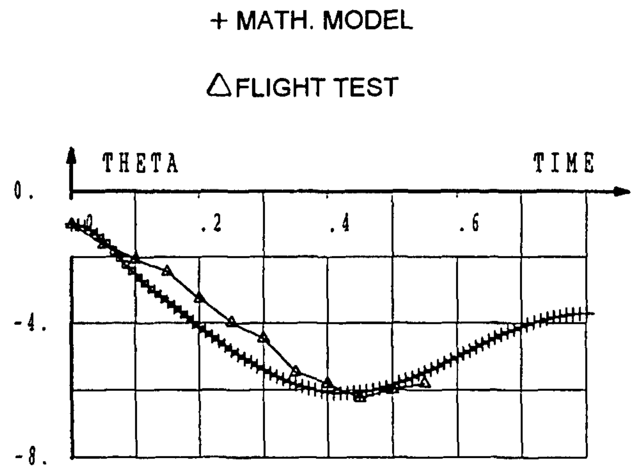


Fig. 9 COMPARISON BETWEEN PREDICTION AND FLIGHT TEST RESULTS

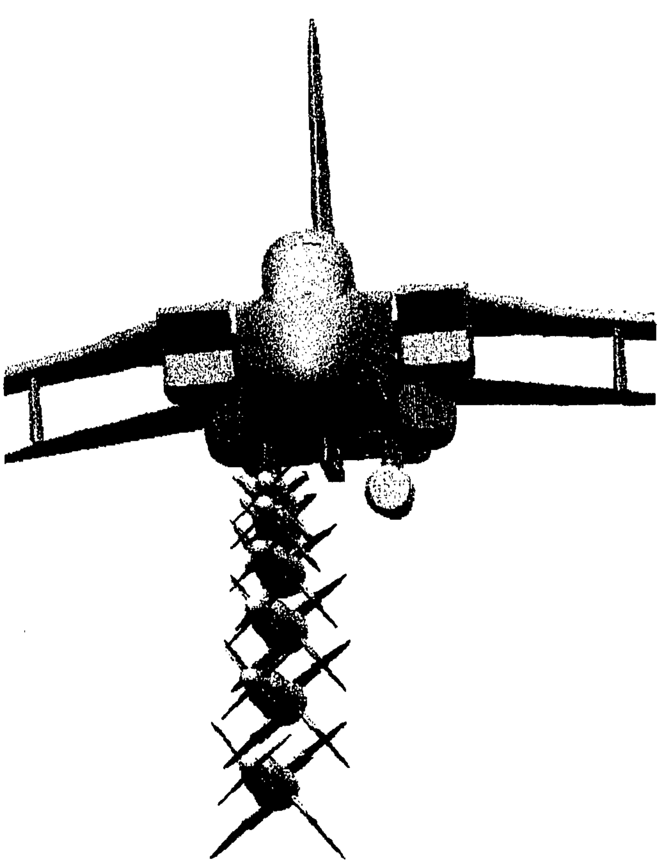


VERTICAL DISPLACEMENT



PITCH ANGLE

Fig. 10 CAD-CATIA MODEL OF BOMB SEPARATION TRAJECTORY



MATHEMATICAL MODEL PREDICTION

FLIGHT TEST RESULTS

TESTING AND PROVING THE GBU-24 LASER-GUIDED BOMB FROM THE U.S. NAVY'S F-14 AIRCRAFT

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Abstract

When the U.S. Navy identified the requirement to carry and employ the Texas Instruments-Raytheon GBU-24 Laser Guided Bomb (LGB) hard target penetrator from the F-14 aircraft, its weapons compatibility/certification engineers had to modify the weapons flight test process which had been in use for determination of F-14 aircraft and Air-to-Ground (A/G) weapons compatibility. That process consisted of beginning tests at low Mach/airspeed in straight and level flight, and continuing tests, at incrementally greater speeds, through the highest Mach/airspeed and steepest flight path angles, with the acceptability of the weapon separation trajectory evaluated through film from aircraft-mounted cameras. The GBU-24, because of its large size and large deploying wing, had to be evaluated through an integrated test and evaluation process consisting of computational analyses, wind tunnel testing, ground testing, flight testing and photogrammetric analyses, used interdependently, to determine the extent of aircraft/weapon compatibility. The test process ultimately led to the authorization for all F-14 variants to carry and employ two GBU-24's on fuselage carriage stations. In addition, the testing led to authorization for launching of an AIM-7 Air-to-Air missile from a fuselage carriage station which was behind the LGB A/G weapons.

Symbols

ALPHA	Angle of attack
C.G.	Center of Gravity
Cm	Pitching moment coefficient about C.G.
CN	Normal force coefficient
Cn	Yawing moment coefficient about C.G.
G	Acceleration due to gravity, 32 ft/sec/sec
GBU	Guided Bomb
KCAS	Knots Calibrated Airspeed
LGB	Laser Guided Bomb
M	Mach Number
P	Weapon roll rate, positive right wing down, deg/sec
PHI	Weapon roll angle, positive right wing down, degrees
PSI	Weapon yaw angle, positive nose right, degrees
Q	Weapon pitch rate, positive nose up, deg/sec
R	Weapon yaw rate, positive nose right, deg/sec
THE	Weapon pitch angle, positive nose up, degrees
X	Weapon C.G. location, positive forward, ft.
Y	Weapon C.G. location, positive right, ft.
Z	Weapon C.G. location, positive down, ft.

Introduction

The U.S. Navy's F-14 Precision Strike Program was formulated to expand the A/G weapon delivery capability of the F-14A/B/D aircraft through inclusion of a self-contained precision weapons capability. To accomplish this, a Forward Looking Infrared sensor and Laser Designator were incorporated in the aircraft, and LGBs were tested on, and cleared for use with these aircraft. The GBU-24 was a particularly difficult LGB to test on the F-14 because of its minimal weapon/aircraft clearance, even in the carriage position, and because of its large deploying aft wing during the weapon's separation from the aircraft. Initial ground fit tests showed that, on the aft fuselage carriage stations, the GBU-24 wing housing (wing in stowed position) was only 2.75 inches from the engine nacelle!

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

Weapon separation wind tunnel testing was conducted with a 5% scale F-14 model in the Arnold Engineering Development Center's (AEDC) 4T transonic wind tunnel. The purpose of the test was to identify which, if any, F-14 weapons stations were suitable for carriage and separation of the GBU-24, how many GBU's could be carried simultaneously, and what length wing latch lanyard would be required to assure safe clearance of the deploying GBU-24 wing from the F-14's nacelles. The test was complicated by the need to account for a free-floating, spring-loaded canard on the nose of the GBU-24, and by the two-position opening sequence for the aft wing on the weapon. An additional purpose of the test was to determine whether an AIM-7 missile could be safely launched from behind a 2000 lb LGB (GBU-24 or GBU-10).

Using the wind tunnel data, separation trajectories were calculated and used to formulate a flight test plan for determination of a safe separation/employment envelope, and to identify the appropriate length wing latch lanyard for weapon wing deployment.

Flight testing was conducted to prove the safe carriage and separation envelope, as well as aircraft carrier launch compatibility. 14 GBU's and 2 missiles were separated on 14 aircraft flights, leading to authorization for simultaneous carriage of two GBU-24's on diagonally opposed fuselage weapon stations, to supersonic Mach numbers and flight path angles down to 45 degrees for all F-14 variants, and for carriage/launch of an AIM-7 missile from behind forward-mounted LGB weapons.

Description of Aircraft

The F-14 Tomcat is a supersonic, two-seat, twin-engine, swing-wing air-superiority fighter designed and manufactured by the former Grumman Aerospace Corporation. The F-14A is powered by two Pratt and Whitney TF-30-P-414A engines and is fitted, primarily, with analog avionics. The F-14B has avionics similar to the F-14A but is powered by General Electric F110-GE-400 engines. The F-14D is also powered by F110-GE-400 engines, and is fitted with digital avionics and a dual chin pod designed to house the Infrared Search and Track System (IRST), as well as the Television Camera Set (TCS) which is also found in the F-14A/B single chin pod. For Air-to-Air missions all F-14 variants employ Phoenix, Sparrow, and Sidewinder missiles and an internal 20 mm cannon. For A/G missions all F-14 variants employ conventional ordnance. The A/G weapons are carried on four fuselage stations (stations 3, 4, 5 and 6 as shown in Figure 1) using weapon rails equipped with BRU-32 bomb racks. Cameras were installed on the test aircraft to record weapon separations. The test aircraft were representative of fleet aircraft. They were instrumented to provide telemetry and data recording of various aircraft, GBU-24, and AIM-7 missile parameters, including airspeed, angle-of-attack, accelerations, angular rates, and more.

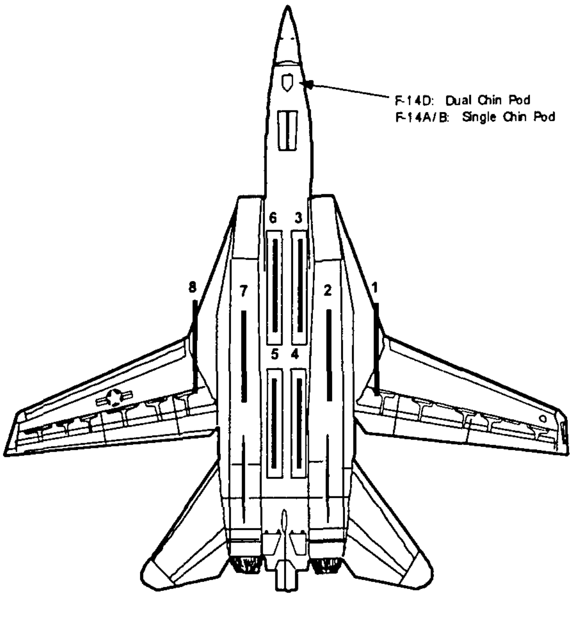

Figure 1. F-14 Aircraft Weapons Carriage Stations

Description of GBU-24

The GBU-24 is a 2000 lb class Paveway III LGB (third generation development of laser guided munitions) which homes on energy reflected off a target illuminated by a suitable airborne or ground laser designator. It consists of a forward-mounted guidance and control unit, a BLU-109 hard target penetrator warhead (which is thermally coated to reduce the hazard from fire), and an aft fairing which directs airflow around the aft airfoil group assembly. An adapter mounted to the top of the weapon consists of a hardback designed to interface with the F-14's BRU-32 bomb rack. The wings of the airfoil group, upon release, travel to 20 degrees deflection for the first two seconds and then extend fully to 70 degrees. Figure 2 depicts the weapon with its various components, and Table I identifies some of the weapon's key parameters.

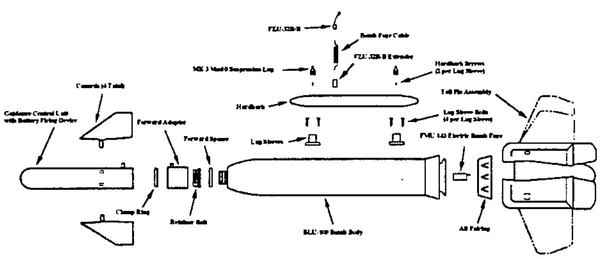

Figure 2. GBU-24 (Paveway III) LGB

Table 1 Key GBU-24B/B Parameters

Parameter	GBU-24B/B
Weight	2380 lb.
Store length	169.69 in. (14.14 ft.)
Canard Span	39.25 in.
Wing Span	wings stowed: 36.0 in. wings 20 deg: 55.75 in. wings 70 deg: 80.36 in.

When the weapon is released, the bomb rack ejects it away from the aircraft carriage station, pulling all lanyards and, thereby, activating the fuze, initializing the weapon and releasing the spring-loaded wings. For the first two seconds after release, the canards are free-floating

For the flight tests, Separation Test Vehicles (STV) were used, differing from the actual weapon only with respect to inert warheads and inert guidance and control units (with operationally representative canard control shafts).

Ground Tests

Initial fit tests of the weapon on the aircraft showed that the weapon's canards extended, laterally, beyond the aircraft fuselage centerline, resulting in canard overlap when weapons were loaded side-by-side. However, one GBU-24 on a forward station, and one on an aft station resulted in an acceptable fit. When loaded on station 5 (aft starboard), the horizontal clearance between aircraft nacelle and the GBU-24 upper outboard wing tip was 2.75 inches. The questions that needed resolution, then, were:

> Which combination of stations would be acceptable (stations 3 and 4, stations 3 and 5, stations 4 and 6, or stations 5 and 6)?
>
> What length wing latch lanyard was required, to assure clearance between the opening GBU-24 wing and the aircraft nacelle ? (Too long a lanyard could also pose a problem with respect to inducing a nose down pitching moment)

Testing by trial and error was clearly unacceptable due to risk and cost. Analytical computations of predicted separation trajectories were required, and wind tunnel data were needed as inputs to those computations.

Wind Tunnel Testing

A 5% scale wind tunnel model of the F-14 was available and used for this test; F-14A/B and D configurations were tested. In the AEDC 4T tunnel, the aircraft model is mounted inverted on a special support system attached to the floor of the test section. The weapon model is mounted on a separate sting which is attached to the top of the test section. The weapon can be placed at selected points from close to the actual carriage position to points clear of the aircraft interference flowfield to measure the forces and moments at those positions. The weapon support sting can also be moved, via computer calculated positions based on measured forces and moments, throughout the weapon's trajectory. Figure 3 shows the GBU-24 above the parent F-14 aircraft.

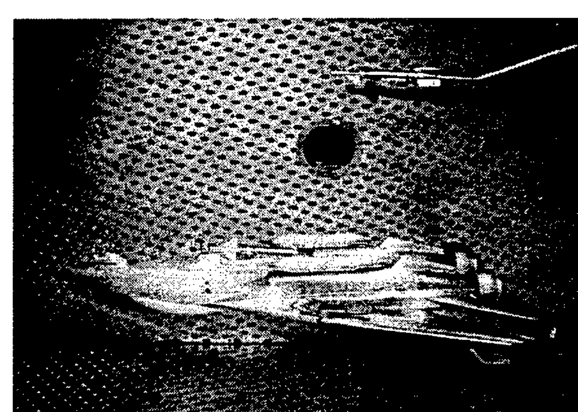

Figure 3. F-14/GBU-24 in AEDC 4T Wind Tunnel

Freestream Tests

Prior to installation of the aircraft model in the wind tunnel, freestream data were obtained with a 5% scale model of the GBU-24. At that small a scale it was impossible to model the weapon's floating canards; the initial plan was to test the weapon with fixed canards, only. However, experience from previous U.S. Air Force compatibility testing of the F-15 aircraft and the GBU-24 had shown that GBU-24 wind tunnel testing required identical runs both with and without canards to quantify the effects of the floating canards on the trajectory. Subsequent U.S. Navy wind tunnel testing of another aircraft model, with 10% scale GBU-24's which actually had floating canards, showed that even at that larger scale it was not feasible to duplicate the dynamics of the canards. Three model configurations were, therefore, tested to gather freestream data:

a. Wing stowed, fixed canards
b. Wing stowed, canards off
c. Wings deployed 20 degrees, fixed canards

Captive Trajectory Tests

Prior to the wind tunnel entry a comprehensive test matrix had been formulated which was well in excess of the amount of testing actually required. Not knowing the direction of weapon yaw or lateral motion, not knowing the direction/magnitude of weapon pitch attitude, and not knowing which actual aircraft carriage stations would finally be used, the matrix had to account for all possibilities. Captive trajectory tests were conducted to answer some of those unknowns and to allow the matrix to be reduced. One of the most significant results of the captive carriage tests was the identification of aircraft stations 3 and 5 as the best combination for carriage of 2 weapons.

Carriage Loads and Grid Tests

The most critical parameters influencing a weapon's initial separation trajectory are the pitching, rolling and yawing moments at carriage. While some aerodynamicists choose to accept as carriage loads, the forces and moments measured on a weapon brought to the closest possible position near carriage by the wind tunnel's captive trajectory sting, U.S. Navy engineers have observed significant differences in loads measured at carriage versus "very close" to carriage for some designs. Therefore, carriage loads tests were obtained by mounting an instrumented weapon model in the actual carriage position. At the same time grid data were obtained for the store on the aircraft station not being tested for carriage loads. Grid sweeps were conducted at various pitch and yaw angles as determined from the captive trajectory tests. The GBU-24 configurations, for which grid data were measured, included canards-on , canards-off, wings-stowed and wings in the 20 degrees open position. On completion of the GBU-24 grid sweeps, an AIM-7 was mounted on the aft center fuselage station to measure carriage loads with 2000 lb LGB's on aircraft stations 3 and/or 6. Grid sweeps and captive trajectory tests were subsequently performed for the AIM-7, again with single or dual 2000 lb LGB's on the forward aircraft carriage stations. Figure 4 shows the F-14 model with the AIM-7 behind two 2000 lb GBU-10's.

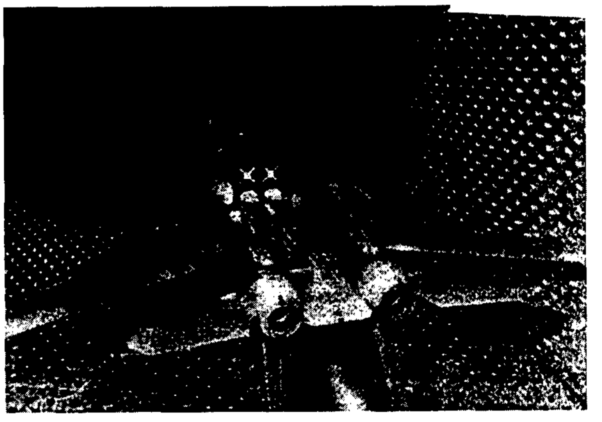

Figure 4. F-14/AIM-7 in AEDC 4T Wind Tunnel

Aircraft Static Ejection Tests

The two characteristics of the GBU-24 which greatly complicated the ability to analytically determine separation trajectories, even with wind tunnel data, were the free floating canards and the moving wings. It was felt that Computational Fluid Dynamics (CFD) analyses could be used to determine the local upwash and sidewash angles at the GBU-24 nose, and thus, could help in computing canard deflection angles. But given the complexity in getting to that point, accompanied by the uncertainty in the CFD results, it was decided to evaluate canard dynamics via the aircraft mounted cameras during flight testing. The wing opening effects, on the other hand, had to be well-defined prior to flight because of the criticality of preventing the wing from contacting the aircraft

during separation. The GBU-24 manufacturer provided data regarding initial wing opening rate, and other data were available from F-18/GBU-24 compatibility flight tests. The average initial wing deployment delay was supposed to be 53 msec, and the statistically fastest possible initial deployment rate was 300 deg/sec. To evaluate the opening dynamics more precisely, static ejection tests were conducted, and cameras used to record the movement of the weapon and its components. Twelve static ejections were conducted from aircraft station 5. Nine and eighteen inch wing latch deployment lanyards were selected for evaluation to provide approximately six and twelve inches of vertical weapon travel, respectively, prior to wing deployment. The extensions were built into the lanyards by either doubling up the extension and encasing it in heat shrink wrap, or by putting the extension into a loop and securing the loop with standard ordnance tape. In both cases, the lanyard pulled to its full extended length prior to pulling the wing deployment latch; the lanyards parted at a weak link, leaving a short length attached to the suspension unit, while the majority of the lanyard remained with the weapon. The photogrammetric data from these ejection tests were used to modify the 6 degrees of freedom separation model of the weapon. The tests led to final selection of the 9 inch extended lanyard for GBU-24's carried on aircraft station 5.

Captive Carriage Tests

Prior to separating the weapons from the F-14, in-flight, captive carriage flight tests were conducted through the flight envelope. To impose all foreseeable environments on the weapon, maneuvers included aircraft clean and dirty stalls, steady heading sideslips, pitch and yaw doublets, accelerated rolls, wind-up and wind-down turns, a throttle chop, a steady push, an acceleration run, a simulated dive delivery, and high dynamic pressure runs. Post flight evaluation of the onboard camera film showed no adverse canard motion, and all arming wires and lanyards returned intact. Following one captive carriage flight, weapon inspection revealed failure of the aircraft station 5 GBU-24 metal retaining ring which surrounded the forward part of the aft fin fairings; the failure occurred at the screw clamp resulting in detachment of the band and separation from the store. The extended wing release lanyard bound under the fairing. Weapons were tested on aircraft stations 3 and 5 for several further hours. No additional problems were evidenced and the damage on the first flight was subsequently deemed to be an anomaly. Authorization was given to proceed with separation flight testing, with carriage up to supersonic airspeeds/Mach Numbers.

Separation Flight Tests

For the flight testing, data were obtained from aircraft mounted high-speed cameras, aircraft onboard instrumentation (recorded onboard as well as telemetered), a sensor unit installed in the weapon tail fuze well, cinetheodolites and ground tracking mounts, chase aircraft cameras, and aircrew recorded data. The sensor unit in the weapon provided three axes accelerations and pitch, roll and yaw rates. During the flights the aircraft parameters were observed real-time, as were weapon accelerations and angular rates. The camera films provided the time histories of the weapon motion following release; the aircraft and weapons were marked with photo targets to permit photogrammetric analysis after the flight.

Figure 5 depicts the cameras and their locations on the aircraft. The cameras located at stations 2 and 7 were housed in converted fuel tanks, referred to as Fuel Tank Camera Pods (FTCP). A flash system was used to detect initial weapon motion; it improved he photogrammetric analysis/solution by correlating first movement, viewed via the cameras, with and without event markers. The onboard cameras provided the bulk of the separation data. All cameras were Photosonic Model 1PL except for the nose cameras, which were Photosonic Model 1VN. Camera speed was 200 frames per second and provided approximately 40 secs of film run time. All aircraft cameras, except the nose camera, had Interservice Range Instrumentation Group (IRIG) standard time displayed on the film for accurate data correlation.

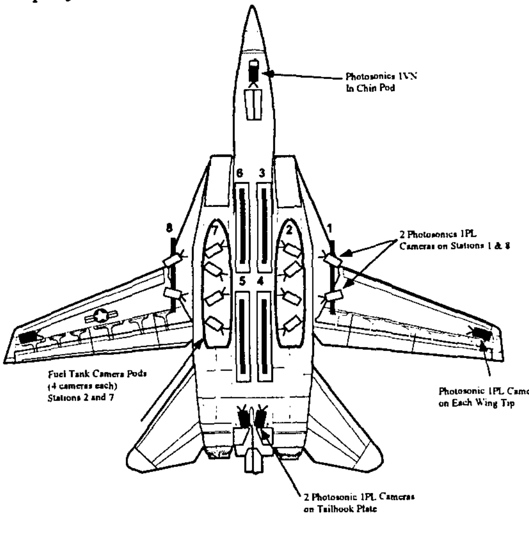

Figure 5. F-14 Test Aircraft Camera Locations

Detailed evaluation of the various wind tunnel configurations and worst case trajectory predictions, considering canard deflection and wing position, showed that separation of a GBU-24 from aircraft station 3 at M=.82 would be a minimal risk test point. Thus the first flight test was a separation from station 3 at 500 KCAS, M=0.8.

Figure 6 shows a comparison of the predicted weapon attitudes, during separation, with the attitudes obtained through integration of the rates telemetered from the weapon sensor unit. The prediction was computed by using the canards-on wind tunnel test data. U.S. Navy past experience has shown that, typically, it is very difficult to match weapon roll attitude precisely, and so the roll mismatch did not cause concern. On the other hand, pitch and yaw can be matched extremely well, and the prediction, in this case, was unsatisfactory due to the significant mismatch in pitch.

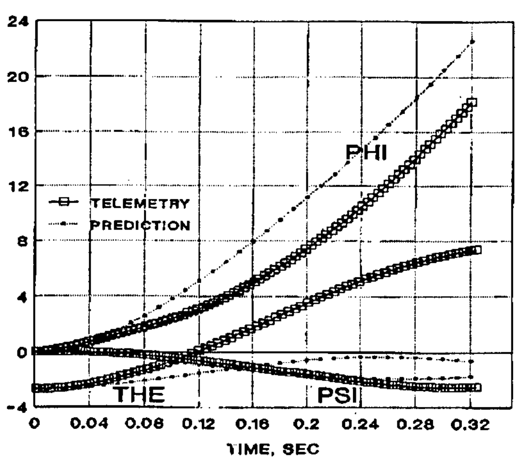

Figure 6. GBU-24/F-14 Station 3 Trajectory

Since the difference in pitch attitude could, perhaps, have been attributable to the canard effect, a predicted trajectory was computed with the canards-off wind tunnel data. Figure 7 shows the difference in freestream characteristics between the canards-on and canards-off configurations. Removing the canards changes the weapon's pitch characteristics from unstable to stable, although the normal force does not change significantly.

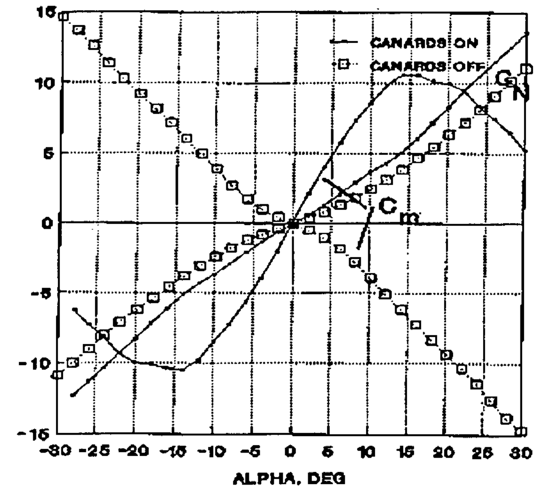

Figure 7. GBU-24 Freestream Wind Tunnel Data

Figure 8 shows the comparison between predicted and actual angular rates using canards-off data for the prediction. Note that the trajectories account for wing deployment; the wings open between 85 msec (0.6 ft) and 170 msec (2.0 ft). The grid and freestream data were interpolated, linearly, during the opening sequence, between the wings-stowed data and the wings-deployed 20 degrees data.

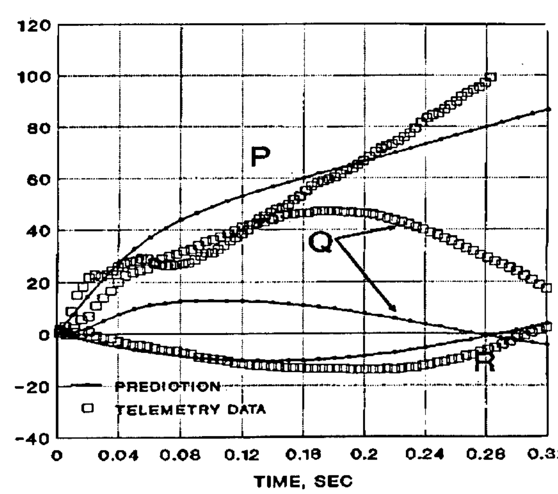

Figure 8. GBU-24/F-14 Station 3 Angular Rates

The poor match in pitch rate was attributed to the aircraft flowfield effect on the canards. Flight test film showed that the canards were deflected nose up in carriage, indicative of a download on the nose of the weapon. Seeking to account for the load on the canards, the canards-off grid pitching moment coefficient was incrementally increased until predicted and actual pitch rates matched. Figure 9

compares the modified predicted angular rates with flight test results.

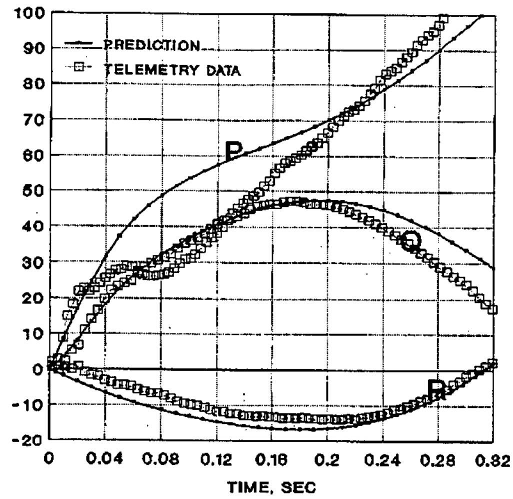

Figure 9. GBU-24/F-14 Station 3 Angular Rates

The corresponding weapon attitudes are compared in Figure 10. The pitch and yaw matches were quite good; predicted roll attitude was approximately 2 degrees greater than was actually experienced in flight.

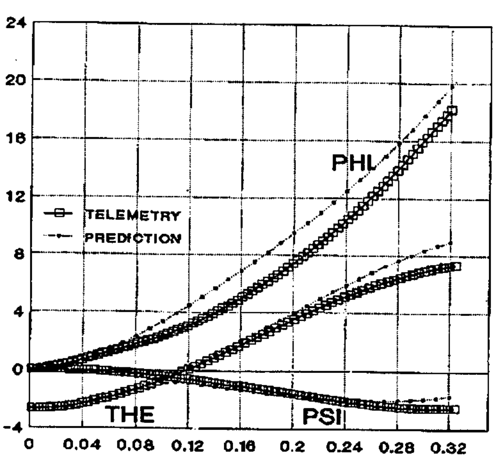

Figure 10. GBU-24/F-14 Station 3 Trajectory

To gain confidence in the validity of analytically predicted trajectories for other flight conditions, the next flight test was conducted at M=0.9. Using the same incremental pitching moment coefficient, based on observation of canard nose-up deflection in carriage at the release condition, angular rates and attitudes were computed and compared with flight test results, with very similar results to those shown above. The weapon again pitched up, with negligible yaw, and a roll build-up due to the weapon wing geometry.

Acceptability of a separation trajectory is well-defined in MIL-STD-1763A (Ref 1), in terms of weapon miss distance from the aircraft and other weapons. The Standard requires that a weapon have positive movement away from the aircraft, and that no portion of the weapon penetrate a predetermined interference boundary of the aircraft (including remaining suspension/release equipment and other weapons). The boundary is defined by a 6 inch encapsulation of the aircraft (in the immediate area where separation is occurring), the ejection rack, and any adjacent weapons. Portions of the weapon already inside the boundary, when in the carriage position, are prohibited from further encroachment. Once outside the boundary, no part of the weapon may re-enter the boundary. Figure 11 shows the actual miss distances for both flights, based on photogrammetrics, and the prediction for the 2nd flight.

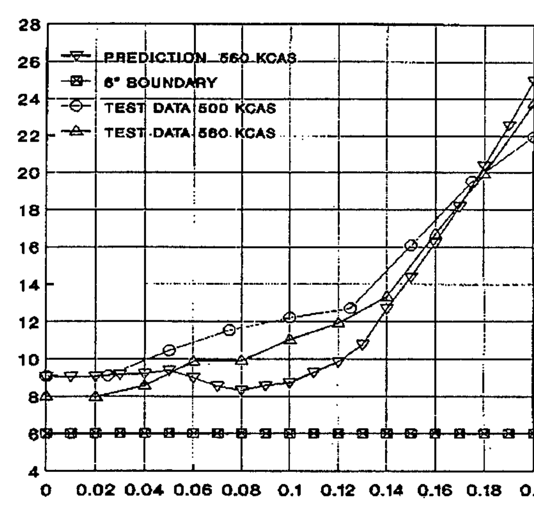

Figure 11. GBU-24/F-14 Station 3 Miss Distances

The conservative prediction seen in the Figure was also seen throughout the test program; predicted miss distances were always somewhat less than actual flight test results, giving confidence to making decisions based on the analytical results. One explanation for the difference is that aircraft motion in reaction to the weapon ejection was not accounted for; predicted weapon trajectories were based on the assumption that the aircraft was fixed in space.

Flight tests were conducted through the transonic and supersonic speed ranges, and all of the separations

from aircraft station 3 were characterized by an initial nose-up pitching moment, negligible yaw, and increasing roll. The separation trajectories remained outside the 6 inch boundary of the MIL-STD, leading to a recommendation to authorize operational use of the weapon on aircraft station 3.

Station 5 separations were higher risk than station 3 because of the weapon's close proximity to the engine nacelle and the extended length wing latch lanyard. M= 0.8 was again selected as the first flight test point, to gain confidence in the validity of the predicted trajectories by releasing at a minimum risk flight condition. The salient characteristics of the separation were a nose-up pitch of approximately one-half the magnitude of that on station 3, a yaw (nose-inboard) approximately 4 times greater than that on station 3, a lateral translation towards the center of the aircraft, and an increased delay in initial wing deployment. The extended lanyard introduced approximately 175 msec delay before wing opening. The analytical trajectory prediction, like that on station 3, was not an acceptable match. The canards-off grid data again provided a closer match than did the canards-on data, but incremental perturbation of the pitching moment and yawing moment coefficients was required to match predicted angular rates to the measured angular rates. The closest match in rates, and, hence, attitudes was obtained with a delta of 1.0 added to the pitching moment, and -2.5 added to the yawing moment. Figure 12 is a comparison of the predicted and measured attitudes.

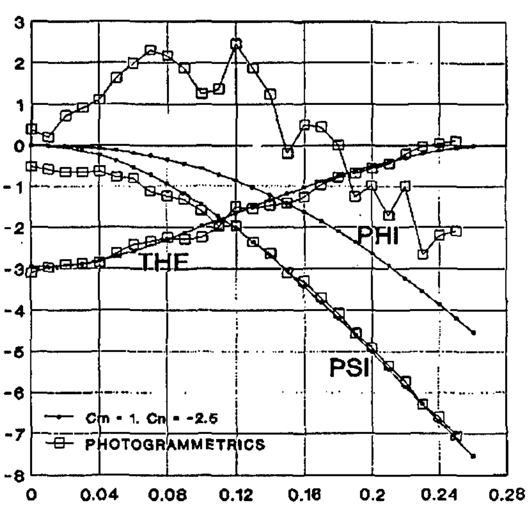

Figure 12. GBU-24/F-14 Station 5 Trajectory

The roll attitudes did not match, but the differences were again small in magnitude. Figure 13 compares the flight test measured miss distance with the predicted miss distances using both canards-on and canards-off grid data. The separation trajectory meets the requirements of MIL-STD-1763A, since the weapon has positive movement away from the aircraft.

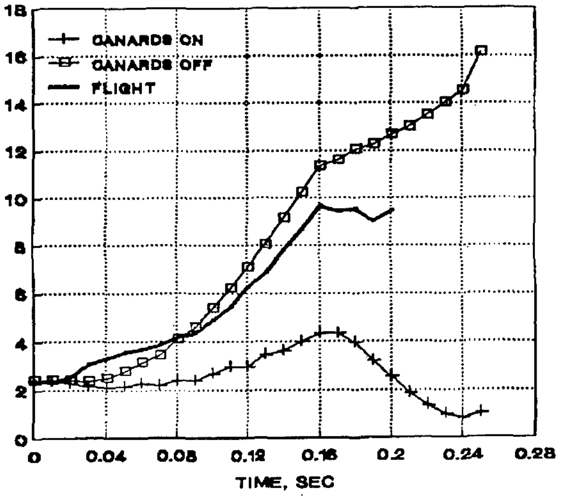

Figure 13. GBU-24/F-14 Station 5 Miss Distances

Flight tests for station 5 separations were conducted through the transonic and supersonic speed regimes. Using the same constant deltas in pitching moment and yawing moment, as previously noted, and using the canards-off grid data, predictions matched flight test attitudes and miss distances extremely well. All trajectories remained within the requirements of MIL-STD-1763A and led to authorization for operational use of the GBU-24 on aircraft station 5.

The overall lessons learned from this test program were:

> For a weapon with free-floating canards, it is essential to perform wind tunnel tests of the weapon without canards, when conducting separation grid tests
>
> When testing for carriage loads data for the same weapon, however, the canards must be on the weapon

An additional goal of this program was to determine the extent of AIM-7 missile compatibility with the F-14 aircraft, when carried and launched from the aft fuselage centerline station, given a 2000 lb LGB on

one or both of the forward aircraft stations. Based on previous experience with the F-14, this was a configuration which could not be proven by simply flight testing. The two types of 2000 lb LGB's authorized for use on the F-14 were considered: GBU-24 and GBU-10. (The GBU-10 is a 2000 lb class Paveway II LGB). In the case of the former, a single weapon on aircraft station 3 had been tested in the wind tunnel, as well as dual GBU-10's on stations 3 and 6, with the AIM-7 in the aft missile station. The AIM-7 was tested for freestream data, carriage loads, captive trajectories and grid data. The most critical mixed weapons configuration, from a separation consideration was found, from the wind tunnel data, to be dual GBU-10's on stations 3 and 6. Two flight tests were performed; the first at transonic speed, the second at supersonic speed. Since the missile did not have floating canards or a deploying wing, the analysis problem was relatively simple and straightforward. The only complexity, really, was modeling the missile's control system for the aircraft/weapon separation part of its flight envelope. Figure 14 shows a comparison of the measured roll and pitch attitudes, and the attitudes predicted with the wind tunnel data. There was no yaw.

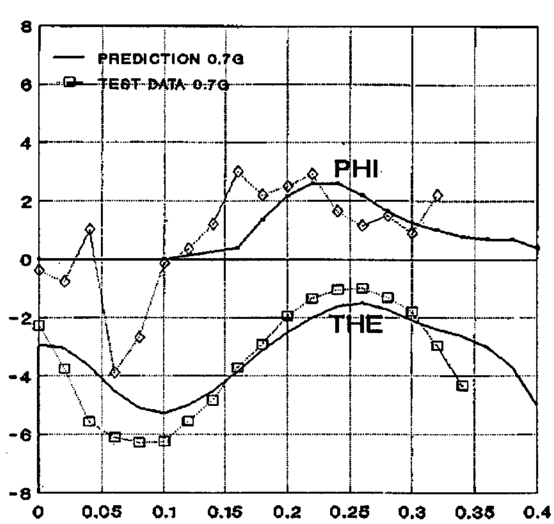

Figure 14. F-14/AIM-7 Trajectory

Figure 15 compares the measured and predicted vertical and longitudinal displacements of the missile during one of its launches (in a 45 degree dive).

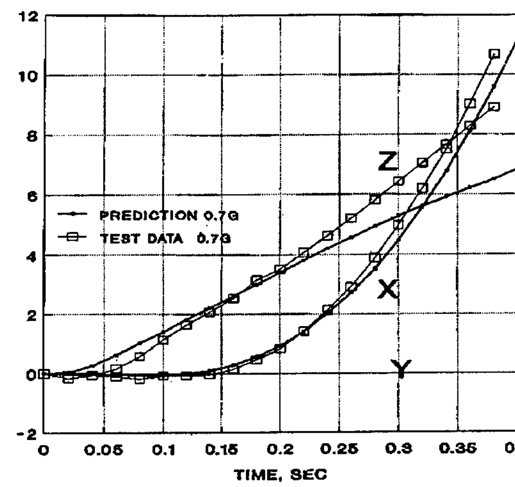

Figure 15 F-14/AIM-7 Trajectory

Conclusion

Determining the extent of compatibility of the GBU-24 with the F-14, and of the AIM-7 missile with the F-14, given 2000 lb LGB's in front of the missile, was a task which could not be accomplished by the old "cut and try" method of testing because of unacceptable risk and cost. Using a combination of computational analyses, wind tunnel testing, ground testing, flight testing and photogrammetric analyses, the U.S. Navy's compatibility/certification engineers were able to clear the GBU-24 for operational use on the F-14. A relatively small number of test assets and test flights were used in clearing the final, large employment envelope; carriage of multiple GBU-24's, and GBU-24 or GBU-10 in combination with an AIM-7 missile was also successfully proven.

References

1. MIL-STD-1763A, Military Standard, Aircraft/Store Certification Procedures, 15 June 1992

DEVELOPMENT, TEST AND INTEGRATION OF THE AGM-114 HELLFIRE MISSILE SYSTEM AND FLIR/LASER ON THE H-60 AIRCRAFT

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SUMMARY

The Hellfire Missile System (HMS) and a nose mounted FLIR with laser designator system were selected as integration candidates on H-60 derivatives based on a new fleet weapons requirement. Naval Air Warfare Center Aircraft Division (NAWCAD) Patuxent River conducted ground and flight tests to structurally qualify the HMS and FLIR systems and evaluate their integration into the H-60 airframe. Three ground firings and 45 hours of flight test (including six missile firings and eight launcher jettisons) were conducted in 1995 during the technical feasibility phase and 60 test flight hours were flown in 1997 during the system integration phase. In-flight jettison and missile firing test planning utilized a six degree-of-freedom simulation to

develop the minimum number of test points to clear the desired envelope while managing risk. Testing demonstrated the successful structural integration of the HMS and FLIR systems. Testing then proceeded with integration of the functional FLIR and HMS. The integration test program fired 6 missiles at fixed and moving targets, under day and night conditions over land and water using the FLIR/LASER for tracking and autonomous designation. Integration development and testing utilized specialized U.S. Army Hellfire instrumentation as well as the Laser Designator Weapons System Simulator (LDWSS) modeling tool. LDWSS was used to simulate launch conditions and engagement scenarios, predict missile launch transients and trajectories, and identify launch constraint and laser self-designation issues. The simulation tools and test methods employed minimized test flights and required assets, resulting in an efficient certification of this weapon system for fleet use.

1. INTRODUCTION

The Left Hand Extended Pylon (LHEP) on the SH-60 was qualified for carriage of gravity dropped stores (fuel tanks, torpedoes, Penguin missile) during the initial aircraft design program. When U.S. Navy fleet requirements dictated that the SH-60 derivative platforms have an additional weapon capability as well as a FLIR capability, the Hellfire Missile System (HMS), along with Commercial-Off-the-Shelf FLIR and LASER technologies were identified as candidates for evaluation. Necessary tests were identified to determine the aircraft/system compatibility of a basic FLIR HELLFIRE SYSTEM (FHS) installation prior to proceeding with full system integration. During the technical feasibility/compatibility phase, Naval Air Warfare Center Aircraft Division (NAWCAD) Patuxent River conducted ground and flight tests to certify the FHS on SH-60 series airframes with respect to structural compatibility, store safe separation, and safety of flight [reference 1]. The integration phase of the program followed with an evolutionary, fully integrated FHS that was evaluated during additional ground and flight tests in both engineering and mission representative environments.

This paper presents an overview of the development, test, and integration of the FHS on the Navy SH-60 aircraft. Discussion of methodology and test techniques is separated into two sections, the technical feasibility phase and the system integration phase. General test results are discussed as well as some comparison between test results and analysis predictions. Usefulness of simulation tools in this aircraft weapon system integration test program is also discussed.

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

2. TEST AIRCRAFT AND EQUIPMENT

Two different series SH-60 aircraft were used for the test program. The technical feasibility phase was conducted using a YSH-60F and the integration phase was conducted on a SH-60B. Except for mission equipment differences and evolutionary upgrades, these two aircraft are approximately the same, with all relevant features such as external stores stations being identical. Additionally, the FHS configuration evolved between the technical feasibility phase and the integration phase.

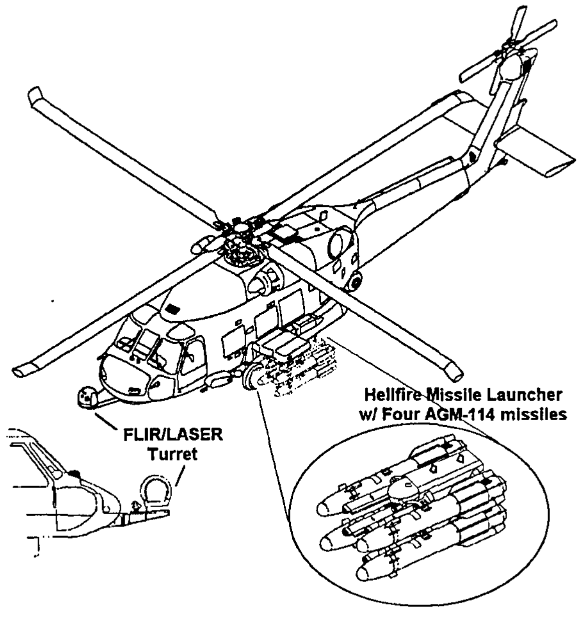

Figure 1. SH-60 Aircraft

2.1 SH-60 Aircraft

The U.S. Navy SH-60 Seahawk (Figure 1), manufactured by Sikorsky Aircraft Corporation, is a twin-turbine engine, four bladed single main rotor, and four bladed tail rotor helicopter with an approximate gross weight of 21,500 lbs. The fully articulated titanium spar main rotor has a diameter of 53.7 ft and provides flapping, lead-lag, and feathering degrees of freedom with elastomeric bearings. The four-bladed tail rotor is a rigid system that is canted 20 degrees from the vertical, providing 2.5% of the total lifting force of the main rotor. The aircraft has an irreversible, fully boosted, stability augmented flight control system that includes a controllable stabilator and autopilot to improve pitch attitude and stability. The aircraft has energy absorbing tricycle landing gear and three external stores/weapons stations, two left and one right, that are each equipped with BRU-14 gravity release bomb racks. Two of the stores/weapons stations, right inboard and left inboard, are located adjacent to the fuselage and provide the capability to carry torpedoes and auxiliary fuel tanks. The third station, integrated into the removable LHEP, provides an additional capability for missiles or forward firing ordnance due to its increased distance from the fuselage (approximately 40 inches outboard of the fuselage). The test aircraft were modified by having a permanent nosemount installed that allowed attachment of the FLIR/LASER mission kit assembly. The LHEP was functionally modified to add MIL-STD-1760 cabling/umbilical for the MIL-STD-1760 Hellfire launcher, a hardpoint for the umbilical emergency jettison disconnect lanyard, and necessary access panels. Additionally, the test aircraft were equipped with instrumentation which included a pitot-static boom mounted on the starboard forward fuselage, flight control position indicators, high speed film cameras along the port side, strain gages, accelerometers, pressure transducers, thermocouples, and data recording and telemetering equipment.

2.2 FLIR Hellfire System (FHS)

The FHS system used for the technical feasibility phase consisted of the nose mounted FLIR/LASER, the M299 missile launcher, AGM-114 missiles, and the SH-60/Hellfire missile launch test kit (HLTK). The FHS system used for the integration phase replaced the HLTK with the fully integrated Stores Management Unit (SMU) and software, Power Control and Distribution Units (PCU & PDU), and a Hand Control Unit (HCU) for operating the FLIR/LASER. A video cassette recorder (VCR) was also added to record FLIR video and cockpit communication.

<u>FLIR/LASER</u>

The FLIR/LASER consisted of the optical, electronic, and mechanical elements required for thermal imaging, laser ranging/designating, and directing the sensor line-of-sight (LOS). The components were housed in a turret unit (TU) that operated on a two-axis gimbal attached to the nose mount. The second generation FLIR receiver provided thermal imaging by collecting infrared (IR) scene radiation and converting it into a video signal while the laser range designator (LRD) assembly provided rangefinding and targeting for NATO laser guided munitions such as the Hellfire missile. The TU processor used electronic image stabilization to maintain FLIR image quality in the helicopter vibration environment and the LRD optics contained an

image motion compensation mirror designed to maintain FLIR/LRD line-of-sight alignment. The TU weighed approximately 114 lbs and was controlled by the FLIR Electronics Unit (EU), separately mounted inside the aircraft cabin. Alignment of the LRD LOS with the FLIR LOS was accomplished prior to flight by attaching a Boresight Module (BM) to the nose mount and rotating the TU to the boresight position. Ground and flight tests during the technical feasibility phase used a non-functioning TU representative of the operational unit in size, weight, and mass moments of inertia.

M299/M272 Hellfire Missile Launcher

The M299 Hellfire Missile Launcher (HML) was an updated version of the M272 launcher used on current U.S. Army and U.S. Marine Corps (USMC) aircraft. The mechanical structure of the M299 (Figure 1) provided a stable platform capable of carrying and rail launching from one to four Hellfire missiles. Unlike the M272, the M299 contained numerous electronics onboard the launcher and had an updated MIL-STD-1760 interface, while increasing launcher weight by only 3 lbs. Empty, the M299 launcher weighed 143.3 lbs, and with four missiles loaded had dimensions of 64 in. long, 22 in. wide, 29 in. tall and weighed 543 lbs. M272 launchers ballasted to the M299 configuration were used for the jettison flight tests as non-recoverable assets. The M299 launcher was used for all captive carriage and live fire flight tests.

The HML's were attached to the aircraft via the BRU-14 bomb rack on the LHEP. The launchers were suspended from two suspension hooks 14 in. apart that engaged two suspension lugs on the top of the launcher hardback. Sway braces on the bomb rack were adjusted against the launcher hardback to prevent lateral movement of the launcher. The MIL-STD-1760 electrical connector of the launcher umbilical was secured to the pylon by an emergency disconnect lanyard that allowed it to separate from the launcher during jettison. The launcher was not capable of independent missile jettison.

AGM-114 Hellfire Missile

The AGM-114 Hellfire missile (Figure 2) is a laser guided missile designed for use against hard point targets. Hellfire can be employed in air-to-air roles against other helicopters; surface-to-surface against armor and ships; and air-to-surface against armor, ships and bunkers. Guidance is provided through automatic terminal homing on the laser signal reflected from a laser designated target. Hellfire uses a shaped charge warhead to defeat individual hard point targets with minimal exposure of the delivery vehicle to hostile fire.

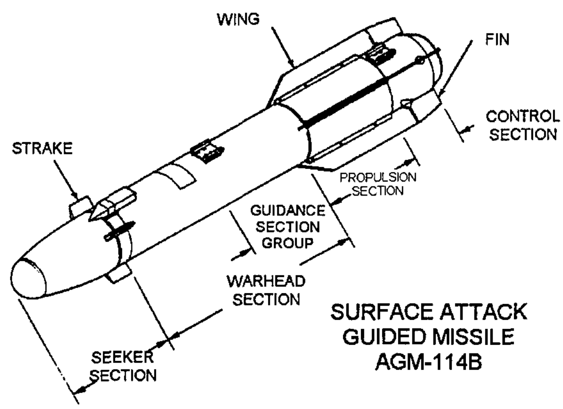

Figure 2. AGM-114B – Hellfire Missile

The AGM-114 consists of five major sections: seeker, warhead, guidance, propulsion, and control. The AGM-114B model is currently used by the USMC and has an autopilot for low visibility conditions, minimum smoke motor, and a shipboard-qualified safe and arm device (SAD) for the motor. The AGM-114K model features dual warheads (to defeat reactive armor), an electronic safe arm fuse, electro-optical countermeasures hardening, and an externally programmable guidance section for trajectory shaping/seeker logic changes. The AGM-114K contains both pulse rate frequency and alternate code capabilities. The AGM-114K also contains a shipboard compatible SAD. The AGM-114 weighs 99 lbs, has a diameter of 7 in, and a length of 64 in. Additionally, House Mouse (HM) missiles, developed specifically for the test community, are available to gather various missile system data. The HM missiles are tactical missiles that have the warhead and motor removed, but retain the seeker section. The aircraft system recognizes the HM as a tactical missile. HM missiles can be configured to monitor specific test data parameters such as seeker gimbal angle. This test used production AGM-114B and AGM-114K missiles, production AGM-114B and AGM-114K missiles modified with inert warheads, inert motors, and instrumentation, inert training missiles, dummy missile shapes for emergency jettison tests, and AGM-114 HM's.

Hellfire Launch Test Kit (HLTK)

The HLTK consisted of a Toshiba T6600C lap-top type computer and associated interfaces to the aircraft and launcher. During the technical feasibility, the HLTK was used to control the HMS with minimal electrical integration and interface to the aircraft. The HLTK was capable of controlling and monitoring the launcher and up to 4 missiles. The HLTK provided the following information: master arm status, acquisition mode, launcher and missile Built-In-Test (BIT) in progress and BIT results, missile launch status, primary missile ID, launcher present/absent, launcher safe/armed status, individual launcher rail latch status, missile type, seeker type, missile state, individual missile launch status, and missile away.

Stores Management Unit

The SMU was designed to monitor, command, and control the M299 Hellfire launcher and the Hellfire missile(s). The SMU was the bus controller for the MIL-STD-1760 weapons; this bus provided the interface between the SMU and the M299 Hellfire launcher. The weapons bus traffic included command, control, and navigational data for stores and sensors, and the routing of stores information to the FLIR EU for display on the Attack page of the operator's Multi-Function-Display (MFD). The SMU received navigation data via the MIL-STD-1553 avionics bus, command information from the FLIR via the weapons bus, and control inputs via the HCU. The SMU also controlled the fixed missile firing sequence of lower outboard, lower inboard, upper outboard, upper inboard.

3. TECHNICAL FEASIBILITY PHASE

Ground and flight tests acquired aircraft compatibility data as part of the structural and safe separation evaluation of the FHS on the SH-60. Ground tests consisted of a static pull test, Ground Vibration Tests (GVT), electrical checks, Electromagnetic Compatibility (EMC) evaluation, and ground missile firings. These tests were designed to provide enough information to evalulate concept feasibility prior to proceeding with the flight tests. Flight tests consisted of captive carriage, launcher jettisons, and missile firings requiring approximately 45 flight hours. Results of the technical feasibility phase were used to make a recommendation for proceeding with the integration phase.

3.1 Ground Tests

3.1.1 Proof Load Test of FLIR Support Structure

In order to verify the structural adequacy of the FLIR nose mount, a static proof test was conducted. A load of 1534 lbs (115 % maximum expected load during in-flight/landing operations) was applied at the center of gravity (CG) of the FLIR shape using a hand operated hydraulic actuator and a load cell. Output of the FLIR support structure strain gages was recorded and monitored during the test. The proof load was applied in 10% increments up to 1534 lbs. Input load measured by the load cell was simultaneously recorded with the strain gage output.

3.1.2 Ground Vibration Tests

GVT were performed to determine the natural structural frequencies of the FLIR mount and Hellfire Missile Launcher (HML) installations on the aircraft; the natural frequencies were then compared with the major aircraft forcing frequencies to identify potential vibration related structural problems prior to flight test. Vibration characteristics of the two installations were determined by using an impulse hammer and a random input shaker method. For both methods, a stationary excitation point and roving accelerometer approach were used to apply and measure the inputs and measure the response characteristics. The output data was processed with a Fast Fourier Transform (FFT) analyzer and plotted as transfer functions. The structures were excited with random vibration separately in lateral, vertical and longitudinal directions with various missile and adjacent store combinations. Potential resonances evident in the transfer function were compared to the aircraft forcing frequencies to determine if a ten percent frequency separation was present to preclude the potential for mechanical instabilities and resulting high vibratory stress levels in flight. The required separation was not demonstrated for the HML with 4 missiles loaded. Specifically, a small 17.1 to 17.3 Hz vertical mode was observed which could possibly be excited by the aircraft 4x main rotor frequency of 17.2 Hz at 100 percent Nr. Subsequent ground tests with the rotors engaged produced a maximum overall vibratory level of 1.3 g's which was within the range of previous data obtained for similar, structurally acceptable installations on the LHEP, thus allowing progression to captive carriage flight tests.

3.1.3 Ground Missile Firing Tests

Three ground missile firings were conducted from the aircraft to determine the HMS compatibility with the LHEP and surrounding aircraft structure. Stress, vibration, thermal, pressure, and store/aircraft separation data were acquired during each missile launch. The helicopter was positioned 7° nose-up on a platform 44 inches above ground level with the LHEP extending over the edge, providing approximately 50 inches of lower missile to ground clearance and minimum rocket motor blast ground reflections. One missile was fired from the upper inboard station, the lower inboard station, and the lower outboard station in the Lock-On Before Launch (LOBL) mode. The missile impact zone was determined by a floating target approximately 3500 meters downrange illuminated by a shore based laser designator. Located next to the laser designator was a laser spot video system capable of displaying the laser energy on the target. Additionally, seeker azimuth and elevation angles were monitored to ascertain accurate missile lock on the target prior to launch.

Aircraft Structure Compatibility

Stress/strain data were incorporated into the aircraft NASTRAN (NASA Structural Analysis) model for component life cycle fatigue predictions. Pressure and thermal (missile plume) data were gathered to verify that overpressure and heat from the rocket motor blast would not adversely affect port side external aircraft features. Maximum temperatures of 480 ° Fahrenheit (F) were observed on the port auxiliary fuel tank skin, but had a short duration of 0.2 seconds during the launch transient. Ground firing tests without rotor wash and forward airspeed resulted in worst case temperatures. The missile temperature plume during ground firing tests was concluded to be benign and not considered a significant risk factor prior to flight tests.

Separation Characteristics

Along with the structural compatibility of the HMS, the separation characteristics of the missile leaving the HML were determined during the ground firings. Pylon flex, missile tip-off angles, missile tip-off rates, missile/aircraft/adjacent store clearances, rotor blade clearance, and missile trajectory information were recorded. Data was analyzed to ensure that the missile did not come too close to any part of the aircraft structure and that the aircraft dynamic structural response to missile firing loads would not put the missile outside of its launch constraints envelope. Ten surveyed, high-speed (400 frames per seceond, fps) film cameras with Interservice Range Instrumentation Group (IRIG) time stamping documented each missile firing. The three onboard cameras (two forward and one aft of the launcher) were also operated during each firing. Camera data provided immediate qualitative information and was post-processed to calculate a 13 camera photogrammetric launch trajectory solution prior to flight tests. Each missile exhibited safe separation characteristics with respect to the airframe and the rotor disk as it traveled down the launch rail and away from the aircraft

Two of the missile firings were conducted with missiles that had angular rate gyros installed in the inert warhead section to measure dynamic response of the launcher and launch transients imparted to the missiles. During launch, pitch, roll, and yaw rate data were recorded as the missile traveled along and off the rail. Data were recorded until the approximately twenty foot long breakaway aircraft/missile umbilical was pulled away from the aircraft. Analysis of these data indicated that the AGM-114 missile experienced no adverse effects when ground launched from the LHEP of the SH-60.

3.2 Flight Tests

3.2.1 Captive Carriage Flight Tests

Thirteen captive carriage flights were conducted to assess the structural impact of the FHS on the SH-60 airframe/LHEP and to evaluate any changes in flying qualities and performance (FQ&P). Various HML missile load configurations were used during dynamic engineering tests and mission related maneuvering flight. In addition to the aircraft instrumentation, one of the inert missiles carried a rate gyro package in the warhead section, one missile was instrumented externally with accelerometers, and the HML was instrumented with accelerometers. Limited telemetry capability was provided on the test aircraft to allow real-time monitoring of critical parameters by engineers on the ground.

Analysis of structural loads and vibration data with FHS installed concluded that integrity of the SH-60 airframe and operability of the FHS would not be adversely affected during typical mission maneuvers. Structural strain data was less than 10% of allowable levels. There was no degradation in flying qualities or performance of the SH-60 configured with

the FHS as compared to the SH-60 configured with a 120 gallon auxiliary fuel tank on the port inboard station, Mk 50 torpedo on the port outboard station, and Mk 50 torpedo on the starboard inboard station. Minimum clearance between the ground and the M299 launcher was also evaluated during vertical landings up to a maximum Rate of Descent (ROD) of 12 ft/sec. No significant launcher to ground clearance issues were observed. The vertical landing data was used to extrapolate and model lower missile/flight deck clearances in the dynamic shipboard environment in support of ship approach envelope development.

3.2.2 Jettison Flight Tests

Prior to test, a 6 Degree of Freedom (DOF) computer simulation jettison analysis [reference 2] was performed to define the jettison characteristics of the HML for use in determining the jettison flight test matrix. The analysis also determined the launcher loading which exhibited the worst case jettison characteristics in terms of minimum aircraft clearance, and the effects of helicopter sideslip and rate of descent. The analysis predicted that the launcher loaded with two missiles, on the upper and lower inboard stations, was worst case. The analysis concluded that the dominant variable affecting movement of the store toward the aircraft was sideslip and that aircraft descent rate would not significantly affect store jettison characteristics. Results of the analysis predicted store/aircraft contact would occur (missile nose with aircraft main mount tire) at a sideslip of -5° with a forward airspeed of 80 knots calibrated airspeed (KCAS).

Eight flights were then dedicated to the jettison of the HML in level flight and autorotative descents. The HML was loaded in the predicted worst case configuration and mass properties were verified to be within the limits of reference 3 for separation testing. The launcher umbilical was connected for all jettisons so that all standard configuration separation forces were present at release. Jettison test flight conditions are presented below in Table 1.

Onboard high-speed (200 fps) 16mm film cameras and a safety chase helicopter with onboard photographer documented each jettison. Safe separation characteristics of the missile/launcher combination were reviewed with respect to aircraft/launcher clearances and compared with the trajectories predicted by reference 2. Film data from the three onboard cameras were used to calculate a photogrammetric solution of the store's trajectory and pitch, roll, and yaw motion about its CG.

Table 1. Jettison Test Flight Conditions

Test Pt.	Airspeed (KCAS)	ROD (ft/min)	Sideslip (degrees)
1	60	0	+1.5°
2	100	50	-1.0°
3	80	0	-2.0°
4	85	0	-6.0°
5	82	1000	-5.0°
6	78	1500	-7.0°
7	82	3000 (Full Auto)	-7.0°
8	80	3000 (Full Auto)	-8.0°

The first four test points were conducted with excellent separation characteristics. Review of onboard and chase film data and the photogrammetric analysis from the first four points showed the launcher/missile store combination falling straight down and away from the aircraft, with stable separation characteristics. Since the first four jettison tests indicated that the jettison analysis was conservative, jettison test points five thru eight were flown with a more aggressive build-up (see table 1) to gather separation data over a less restrictive, more fleet representative envelope. Separation characteristics for test points 5 thru 8 were still excellent; the store exhibited stable characteristics, falling straight down and away from the aircraft. General store motion for all eight jettisons was characterized by clockwise roll (view from aft), pitch up, and left yaw well clear of the aircraft. Higher initial roll rates were observed during the 3000 fpm ROD test points. Figure 3 present the 3 camera, 6 DOF photogrammetric solution of the first jettison test point.

Jettison test data were simultaneously provided to the U.S. Army Rotary Wing Stores Integration (RWSI) project office for validation of the RWSI store separation prediction software. Comparison of the flight test data with the RWSI predictions is reported in reference 4. The general conclusion was that the RWSI software satisfactorily demonstrated its potential as an engineering tool for predicting store separation

characteristics, but needed additional data from other helicopter separation programs to help refine the prediction accuracy of the store's pitch and yaw motion.

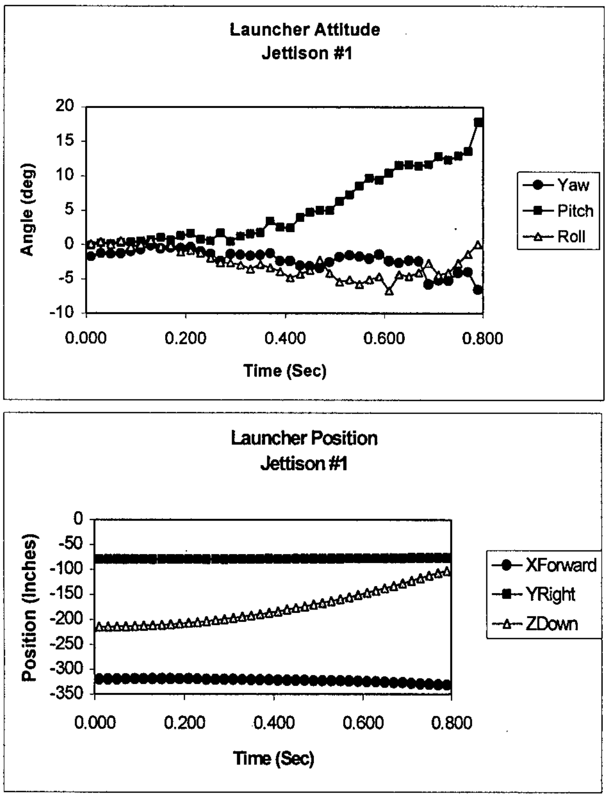

Figure 3. Photogrammetric Solution for Jettison Test Point #1

The in-flight jettison tests demonstrated the capability to successfully jettison the HML/missile store combination from the LHEP on Naval SH-60 series aircraft under the conditions tested. Since the launcher configuration tested was deemed to be the worst case, it may be assumed that other launcher load configurations have as good or better separation characteristics under the same flight conditions. The flight conditions tested were used as the basis for the emergency jettison envelope developed for fleet use.

3.2.3 In-flight Missile Firing Tests

With preliminary analysis of the ground firing separation data indicating that it was safe to proceed, three in-flight missile firings were conducted from the aircraft to further evaluate the HMS compatibility with the LHEP and aircraft structures. Aircraft handling qualities and performance were also evaluated during launch. One missile was fired from the lower outboard station with the aircraft in a hover, one missile from the lower inboard station with the aircraft at 100 knots indicated airspeed (KIAS), and one missile from the upper outboard station with the aircraft at 135 KIAS. The missiles were launched from the aircraft in LOBL mode at a floating target, approximately 4500 meters offshore, that was illuminated by a shore based laser designator. Prior to test the missiles' mass properties (weight, CG, and moments of inertia) were checked against those of unmodified AGM-114B missiles in accordance with [reference 3]. The test aircraft was inspected before and after each in-flight firing to monitor external structural integrity of the aircraft.

Aircraft Structure Compatibility

Aircraft structure compatibility was evaluated during in-flight missile firing tests using the same instrumentation as the ground tests. Accelerometer data, missile overpressure data, and aircraft structures' strain data were provided to Sikorsky for analysis. Maximum temperature of 140° F on the auxilliary fuel tank skin was observed during the lower inboard firing. There were no noticeable effects on the port side aircraft, launcher, or LHEP surfaces due to the missile firings. Firing of the Hellfire missile was deemed to be compatible with the SH-60 aircraft structure.

Separation Characteristics

Along with the structural compatibility of the HMS, the separation characteristics of the missile leaving the M299 launcher were further evaluated during the in-flight firings. Prior to test, a safe separation and tip-off analysis [reference 5] concluded that safe separation would occur within the entire boundary of the SH-60 flight envelope. Pylon flex, missile tip-off characteristics, clearance between the missile, aircraft, and adjacent stores, rotor blade clearance, and missile trajectory were again recorded during the test events. The three onboard cameras along with a safety chase helicopter with an onboard photographer provided 35mm still photos and 16mm high-speed film coverage. Camera data provided immediate qualitative information and was post-processed to calculate a 3 camera photogrammetric solution. Each missile exhibited safe separation characteristics with respect to the airframe and the rotor disk as it traveled down the launch rail and away from the aircraft.

4. INTEGRATION PHASE

Once the technical feasibility phase and FLIR integration had been satisfactory completed, the next objective was to develop an initial firing envelope for the Rapid Deployment FLIR Hellfire System on the SH-60B and to evaluate the Rapid Deployment FLIR Hellfire System helicopter's ability to passively detect, classify, identify, track, and attack surface targets. For this test effort, missile availability was a limiting factor; five AGM-114B's and 1 AGM-114K missiles were available to evaluate total system integration. To supplement testing, Laser Designator Weapon System Simulation (LDWSS), a simulation model developed by the U.S. Army's Missile Command (MICOM), was used to establish an initial aircraft firing envelope. LDWSS is a high fidelity simulation model used by the U.S. Army to determine probability of hit (Ph) and probability of kill (Pk) for varying targets and conditions. LDWSS was updated for the Naval application, including boat/ship targets, target motion/ship response as a function of sea state, and laser characteristics in the ocean environment. Data gathered through this test program was used to verify LDWSS and to create fleet training scenarios.

A captive carry flight test program was established to gather data needed to update the model. Factors accounted for in the LDWSS model that needed to be updated were autotracker robustness, laser energy and laser energy distribution, aircraft pitch and yaw reference angles, and overwater environmental factors. Laser energy data was collected during two separate flight test phases. The first measured laser energy with respect to energy distribution, laser jitter, and laser boresght accuracy. The second portion of laser energy testing measured laser energy in an overwater environment. This test also evaluated how water affected laser energy. It looked at laser energy absorption, energy reflected back to and away from the designator, and salt spray effects on the laser as it left the designator. Pitch and yaw reference angles between the aircraft and missile were also measured and input into the model. This was the first time environmental data for the overwater environment had been gathered for the LDWSS model.

4.1 Updating the Model

<u>Automatic Video Tracker Testing</u>

Flight tests were conducted against ships and/or selected target boats to determine the automatic video tracker (AVT) performance in both centroid and correlation modes while operating in the flight environment from 50 ft above ground level (AGL) to 1000 ft mean sea level (MSL) at 0 to 150 KIAS. The FLIR centroid tracker was designed to track the centroid of the IR image while the correlation tracker was designed to track the IR image or pattern enclosed by the track box. The aircraft was vectored to the target by range controllers on a straight and level approach and positioned at an altitude, range, and airspeed specified in table 2. Once test conditions were established the system operator centered the FLIR reticle on the target, optimized the FLIR image, ensured the on-board video was recording, selected CENTROID (or POINT) TRACK MODE, and depressed and held the AVT track button until the track was established. Pertinent AVT track qualities, including track stability, were then recorded. Throughout the inbound run, the operator qualitatively assessed the offset track function by selecting offset track, slewing the reticle off-axis in all directions at the extreme edges of offset track, releasing offset track to return the reticle to the center of the track position, and then attempting to place the reticle over a specific spot on the target and stabilize. During 200 ft altitude or above run-ins, the aircraft banked left/right, up to 30°/sec (in increments of 10°/sec), up to 45° angle of bank (AOB) for 90° heading change, held 90 ° heading change momentarily, then banked left/right, up to 30°/sec (in increments of 10°/sec), up to 45° AOB for 90° heading change to return to inbound course. During the 50 ft altitude run-in, the aircraft approached the target with wings level. If track was lost during any test, the bank angle was reduced until track could be maintained. The entire test matrix was repeated with CORRELATION (or AREA) TRACK MODE selected.

Table 2. Automatic Video Tracker Test Points

Test Point	Altitude (Ft.) (AGL)	Air Speed (KIAS)	Initial Slant Range (Ft/Km)
1	50/200/1000	70-80	62,336/19
2	50/200/1000	70-80	62,336/19
3	50/200/1000	100-120	62,336/19
4	50/200/1000	100-120	62,336/19
5	50/200/1000	70-80	124,672/38
6	50/200/1000	70-80	124,672/38
7	50/200/1000	100-120	124,672/38
8	50/200/1000	100-120	124,672/38

Inflight Laser Characteristics Testing

Flight tests were conducted against the Electro-Optical Thermal Target (EOTT) to determine the laser spot characteristics in flight. The EOTT is a 20 by 30 foot board with seven 3 ft wide panels which provide a 7:1 aspect ratio. Each panel's thermal signature can be individually controlled. The EOTT panels were heated to their maximum temperature for a maximum delta above ambient conditions, thus improving FLIR recognition of the target. The aircraft was in constant communication with controllers for proper flight path guidance. The aircraft was vectored to a preselected bearing from the EOTT and was positioned at the first altitude, range, and bearing angle described in Table 3. Once test conditions were established the system operator centered the FLIR reticle on the EOTT, optimized the FLIR image, and ensured the on-board video was recording with IRIG B time on. After receiving a cleared to lase call from the controller, the operator designated the target board for 10 seconds using the 1111 laser octal code. During each test event ground personnel recorded laser spot video time-stamped with IRIG B time using Laser Airborne Targeting System (LATS). The LATS system was designed to score the centroid of the laser spot position against the position of the FLIR reticle. The scoring precisely determined laser spot jitter, FLIR to laser boresight, boresight retention, and % laser energy on target. The test was repeated for each altitude, range, and bearing angle in table 3.

Table 3. Inflight Laser Characteristics Test Points

Test Point	Altitude (Ft). (AGL)	Ground Range (Ft.)	Slant Range (Ft.)	FLIR/Acft Relative Bearing (degrees)
1	1,050	3,100	3,300	0, 90, 270
2	3,200	15,900	16,200	0, 90, 270
3	5,100	25,750	26,250	0, 90, 270
4	6,000	30,100	30,700	0, 90, 270
5	10,000	55,000	56,000	0, 90, 270

Overwater Laser Characterization Tests

In order to evaluate laser energy behavior in an overwater environment a 8.5 flight hour test program was established. This involved the test aircraft lasing the target while a UH-1H helicopter equipped with a U.S. Army developed Hellfire instrumentation package flew various missile flight profiles. The instrumentation package consisted of a modified Hellfire missile seeker head that monitored reflected laser energy and a recording system. Test conditions are presented in table 4. Both aircraft were equipped with Mid Atlantic Tracking System (MATS) for proper positioning throughout the test by range control. The target boat, a 56 ft range boat, was also MATS equipped. With the test aircraft lasing the range boat, the UH-1H flew missile level flight profiles from 100 to 1900 ft AGL, in 200 ft increments, collecting laser energy data between 7 and 1 km. To collect data regarding possible laser energy reflected from the water at various grazing angles, laser data was collected onboard the UH-1H while hovering at ranges of 1, 0.5 and 0.1 km at altitudes from 100 to 900 ft AGL with the test aircraft lasing long, short, at the waterline, and aft of the target boat. The test aircraft was again at a range of 4 to 8 km and an altitude of 50 to 500 ft AGL. Prior to performing over-water testing with the UH-1H, the test aircraft directly lased the EOTT while the UH-1H flew the same level flight profiles collecting laser data for reference and equipment checkout.

Table 4. Over-Water Laser Characterization Tests

Test Point	SH-60 AIRSPEED(KIAS)	SH-60 ALTITUDE (FT AGL)	RANGE (KM)
1 [1]	60 - 90	1000	10-4
2 [1]	60 - 90	500	10-4
3 [1]	60 - 90	200	10-4
4 [1]	60 - 90	50	10-4
5 [2]	60 - 90	50 - 500	8 – 6 and 6 - 4
6 [3]	60 - 90	50 - 500	8 – 6 and 6 - 4

Note (1):
a. Fly straight and level inbound to target beginning at 10 km.
b. Lase target every 1 km checking for missile seeker lock-on.
c. Investigate effect of salt environment on laser emissions.

Note (2):
a. Fly multiple racetrack patterns with inbound legs as listed under target range until UH-1H has covered entire inbound leg at given altitude.
b. Position laser spot for optimal energy return.

Note (3):
a. Fly racetrack pattern with inbound legs as listed under target range.
b. Lase tgt adjusting laser spot as coordinated with UH-1H to lase short, long, at the waterline, and aft of the target boat.

Pitch and Yaw Reference Study

To establish minimum launch altitudes and to help determine missile launch constraints and inhibits in pitch and yaw, aircraft data in the form of pitch and yaw reference angles, between aircraft centerline and missile centerline, were acquired. Electronic pitch reference signal voltage accuracy was also verified. To accomplish this, launcher rail angles with respect to aircraft centerline, both average and worst case by intentionally hanging the launcher in an improper manner, were measured. This data was input into the simulation to determine its effect on missile trajectory. These initial condition launch parameters were necessary for the simulation to fly the missile along the proper trajectory for acquiring the desired target. Minimum launch altitudes were then established using the LDWSS model once this data had been incorporated.

Environmental Data

Meteorlogical conditions in the atmosphere are an important factor in calculating laser tranmission from the designator to the target and laser energy returned to the missile seeker. The amount of energy that is totally intercepted by the missile as well as the laser beam divergence along the line of sight path for an overwater environment needed to be quantified. As discribed in reference 6, the air turbulence factors in an overwater environment are strongly driven by the air-sea temperature difference, and to a lesser extent by wind speed, humidity, and other meteorological factors. In general, air turbulence is highest during the day, falls to a minimum in early evening as the air cools to the water temperature, and then increases somewhat late at night as the air cools below the water temperature. Reference 6 provided us with the necessary data to predict laser beam spread and laser energy transmission over the ocean. The original LDWSS model used three values of air turbulence characterized as low, moderate, and high. Those three values were adjusted in the Naval version of the model to represent low, medium, and high turbulence that would be expected in the overwater environment

4.2 Live Fire Tests

The first test event took place at Eglin AFB's C-7 test range. The C-7 test range was a land range specifically instrumented for Hellfire testing. For this live fire event, high-speed video of the missile was taken from launch to impact. High-speed film (aircraft mounted cameras) of the missile leaving the rail were also taken. A ground-mounted silicon vidicon camera was slewed to the target to verify target illumination before missile launch. Time Space Positioning Information (TSPI) data was taken of the aircraft to document exact slant range to the target at missile launch. Throughout the flight path, TSPI data of the missile was also taken. TSPI data of the missile allowed for detection of an in-flight missile failure (missile failure flight path was known). The target for this event was a stationary M-60 tank hulk. Next, four modified AGM-114B's and one modified AGM-114K missile were fired to assess the system performance in a water environment. These missiles were modified by having the warheads removed and inert mass added to the warhead section to simulate the weight, CG, and moments of inertia of a production missile. This modification was conducted in an attempt to not destroy the target. The target for the overwater events was a 56 ft QST-35 target boat modified to represent a PBI patrol boat. Target speed began at minimum steerage and built up to maximum remote controlled speed, approximately 25 knots.

High-speed film cameras were placed on the target to record missile impact. All shots were conducted in the Lock-On-After-Launch Direct (LOAL-D) mode. Prior to each event, a Ph value was calculated using the updated LDWSS model. The first over-water shot mirrored the overland shot as close as conditions would allow. The remaining 4 events were used to verify system performance at various points of the missile fiirng envelope by varying airspeed, range, target speed, and laser delay times.

4.3 Integration Phase Summary

Because of test asset limitations it was impossible to establish a realistic firing envelope by missile firing alone. Therefore, a test program that updated the existing LDWSS model in combination with limited missile firings was established. The LDWSS model was used to establish the initial live firing matrix for this test program and evaluate other scenarios not tested. This tool was successfully used to identify launch constraint and laser self-designation issues, develop employment and tactics, conduct test hazard analyses, and manage technical risk during system development. Efforts are currently underway to update the target data base to include naval targets and to use LDWSS for developing cockpit cards that include tactical information for use by SH-60 aircrews.

5. ELECTROMAGNETIC COMPATIBILITY (EMC)

An EMC evaluation of the FHS was performed to ensure compatibility with aircraft systems and to identify problems with vulnerability to electromagnetic radiation in the local flight test area and in the fleet environment. EMC evaluations were conducted with an HM missile and a M299 launcher installed. Tests were conducted with the missile in the loaded, armed, and ready to launch modes. No intrasystem Electromagnetic Interference (EMI) was noted in either the SH-60 equipment or Hellfire missile and M299 launcher. Additionally, previous Hellfire missile intersystem EMC testing on other platforms, including the AH-64D Longbow system, was reviewed. EMC testing to evaluate compatibility with the shipboard environment was also conducted. All systems operated satisfactorily during this testing.

6. CONCLUSIONS

Certification of the FHS on the SH-60 was successfully completed using a two phase program approach. During the technical feasibility phase, 6 DOF separation models were used to develop test matrices while managing technical and program risk. Flight tests were then conducted and refined based on results and their comparison to simulation predictions. The result was completion of the flight test program using minimal ordnance assets. The integration phase followed a similar approach by using LDWSS and specialized instrumentation that enabled a complete evaluation of the integrated system with a minimum number of missile firings.

Development, test, and integration of the HMS and FLIR/LASER on the SH-60 greatly benefited from the use of computer simulation as an engineering tool Technical feasibility and system integration testing used simulation tools along with traditional flight test methods to efficiently certify this weapon system for fleet use.

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The United States Navy's Integrated Approach to Store Separation Analysis

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1. SUMMARY

The current United States Navy approach to store separation analysis employs a combination of wind tunnel testing, flight testing, and computational aerodynamic analysis. This Integrated Test and Evaluation approach ensures safe separation of stores in a timely and cost effective manner. This approach has evolved over the past decade and is unique because it is performed by an Integrated Product Team (IPT) which belongs to one, physically co-located organization. During the past several years this approach has been responsible for providing considerable time and cost savings to many programs, including the F-18C/JDAM, F-14/GBU-24, F-18C/JSOW, and DC-130/BQM-74 programs. This approach is presently being applied to the F/A-18E/F aircraft/store integration program to both reduce the program cost and ensure the success of the program.

2. LIST OF SYMBOLS

ACFD	Applied Computational Fluid Dynamics
AEDC	Arnold Engineering Development Center, Wind Tunnel Facility, Tullahoma, Tennessee
AIM	Air Intercept Missile
AIMS	Advanced Imaging Multi-Sensor Systems
AMRAAM	Advanced Medium Range Air-to-Air Missile
ASRAAM	Advanced Short Range Air-to-Air Missile
A_i	Influence Coefficient
B_i	Influence Coefficient
BL	Aircraft Buttline, positive outboard, inches
CFD	Computational Fluid Dynamics
CTS	Captive Trajectory System
C_A	Axial Force Coefficient, positive aft
C_N	Normal Force Coefficient, positive up
C_Y	Side Force Coefficient, positive right wing
C_l	Rolling Moment Coefficient, positive right wing down
C_m	Pitching Moment Coefficient, positive nose up
C_n	Yawing Moment Coefficient, positive nose right
EMD	Engineering and Manufacturing Development Phase
FOT&E	Follow On Testing and Evaluation
FS	Aircraft Fuselage Station, positive aft, inches
GBU	Guided Bomb Unit
H	Altitude, feet
IFM	Influence Function Method
IPT	Integrated Product Team
ITALD	Improved Tactical Air Launched Decoy
JASSM	Joint Air-to-Surface Stand-Off Missile
JDAM	Joint Direct Attack Munition
JSOW	Joint Stand-Off Weapon
M	Mach Number
N	Number of Store Segments
NAWC-AD	Naval Air Warfare Center, Aircraft Division
NAWC-WD	Naval Air Warfare Center, Weapons Division
OSD	Office of the Secretary of Defense
P	Store Roll Rate, positive right wing down, degrees/second
PHI	Store Roll Angle, positive right wing down, degrees
PSI	Store Yaw Angle, positive nose right, degrees
Q	Store Pitch Rate, positive nose up, degrees/second
R	Store Yaw Rate, positive nose right, degrees/second
SLAM-ER	Standoff Land Attack Missile - Expanded Response
THE	Store Pitch Angle, positive nose up, degrees
T&E	Test and Evaluation
WL	Aircraft Waterline, positive up, inches
α	Angle of Attack, degrees
ε	Upwash angle, positive up, degrees
ε_i	Upwash angle of segment i, positive up, degrees
σ	Sidewash angle, positive outboard, degrees
σ_i	Sidewash angle of segment i, positive outboard, degrees
θ	Store Pitch Angle, positive nose up, degrees
ψ	Store Yaw Angle, positive nose right, degrees

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

3. BACKGROUND

In the past, store separation was conducted in a very haphazard fashion. Stores would be dropped from an aircraft at gradually increasing speeds until the store came too close to the aircraft or occasionally hit the aircraft. In some cases, this led to loss of aircraft, and made test pilots reluctant to participate in store separation flight test programs.

During the 1960's, the Captive Trajectory System[1] (CTS) method for store separation wind tunnel testing was developed. The Captive Trajectory System provided a considerable improvement over the hit or miss method, and became widely used in aircraft/store integration programs prior to flight testing. However, the CTS method was not utilized in an integrated approach, since the group conducting the wind tunnel test was generally separated both in organization and location from those responsible for conducting the flight test program and determining the safe separation envelope. Furthermore, since relatively small scale models had to be used in the wind tunnel tests, the wind tunnel predictions did not always match the flight test results. As a result, resolution of the wind tunnel/flight test discrepancies was often extremely difficult.

By the late 1970's and early 1980's Computational Aerodynamics had finally matured to the point of providing a solution[2,3,4] for a store in an aircraft flowfield. Rather than revolutionizing store separation methodology, this new capability inspired an ongoing argument among the Computational Aerodynamicists, Wind Tunnel Engineers, and Flight Test Engineers. The Computational Fluid Dynamicists claimed that they could finally replace the wind tunnel. The Wind Tunnel Engineers accused the Computational Fluid Dynamicists of being unaware of the complexity of the problem. Finally, the Flight Test Engineers declared that neither group could provide them with the necessary data to conduct a successful flight test program.

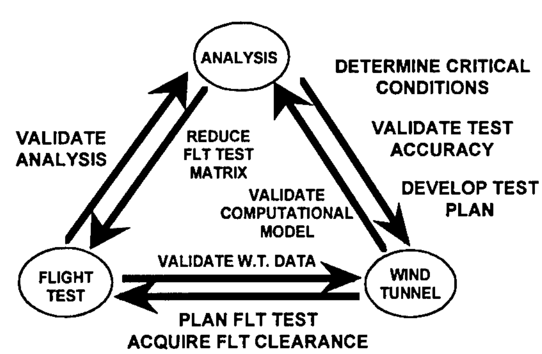
During the same time period the Influence Function Method (IFM) was developed[5]. This method allowed for an estimate of store loads based on the aircraft induced flowfield impinging on the store. This seemed to offer a bridge to the disagreement between the Computational Fluid Dynamics (CFD) and Wind Tunnel communities, since it could provide store loads in the entire aircraft flowfield with just one CFD calculation. However, except for Grumman and the Air Force, this method did not readily gain acceptance in the store separation community. Furthermore, an integrated test and evaluation approach was not truly implemented, since the Flight Test community was still separated both physically and organizationally from the CFD and Wind Tunnel communities.

At that time, the Navy's approach was to use both aircraft and weapon contractors to perform the testing and analysis necessary to clear a new aircraft/weapon configuration. This procedure had several drawbacks, the most serious being that the contractor's involvement usually ended with the start of the flight test program. Therefore the contractor had no means for using the flight test results to improve store separation methodology. Also, no two contractors used the same methodology to predict safe weapon separation prior to flight test.

About ten years ago, the Navy decided to develop a capability/process at the Naval Air Warfare Center, Aircraft Division (NAWC-AD) to conduct the analyses necessary for a store separation flight test program. Without any existing capability in this area, the Navy was able to choose among the best attributes of the techniques used by contractors and the Air Force.

NAWC-AD realized that the three legs of an integrated approach: analysis, wind tunnel, and flight test are intimately related to each other and provide essential information that can improve the product of each group. Not only is the entire program conducted by the same group, but ideally by one individual. The computational aerodynamics, wind tunnel test planning, trajectory simulation and flight clearance for each point in the flight test program are all managed by the same person, who does not have to be an expert in CFD methods or wind tunnel testing, but is competent in their use and more importantly, knows their limitations. This individual not only has the authority, but also the responsibility for ensuring that the flight test program is conducted both safely and cost effectively.

FIGURE 1: UNITED STATES NAVY'S INTEGRATED APPROACH TO STORE SEPARATION



This analysis process has evolved to where the three legs have formed an intrinsic checks and balances system. In order to confirm aircraft/store compatibility, wind tunnel testing, flight testing, and computational analyses are dependent upon and essential to one another. The computational analyses determine the critical conditions to be wind tunnel tested, aid in developing the wind tunnel test plan, and verify the wind tunnel test accuracy; while the

wind tunnel test confirms the computational model. The wind tunnel test is used to acquire a flight clearance and plan the flight test matrix, while the flight test corroborates the accuracy of the wind tunnel test data. The flight test also substantiates the computational analyses, while the computational analyses help reduce the flight test matrix. Figure 1 represents a schematic of the analysis process.

4. DISCUSSION

One of the most critical features that determines a store's separation trajectory is the carriage moments. These moments are principally caused by the aircraft flowfield. Therefore, the first step in separation analysis is to estimate the region of the flight envelope that might have the worst carriage moments. This is done by deriving an estimate of the aircraft flowfield. The primary analytical tool for the purpose of evaluating the aircraft aerodynamics is the linear potential flow program, PAN AIR[6], which has been validated for most of the current Navy aircraft. In addition, changes in aircraft configuration shape such as fuel tanks, pylons, and other stores can be easily modeled/modified.

Although the potential flow codes have demonstrated the ability to predict complex aircraft flowfields in the linear speed regime, pitch/yaw head probe flowfield test data, when available, should always be used to validate the analytical aircraft models. At present, extensive angularity data are available at various Mach numbers and aircraft attitudes for the A-6E, AV-8B, F-18C/D and F-18E/F aircraft, and a limited set of data exists for the F-14. The angularity data are usually acquired at the AEDC 4 by 4 foot and 16 by 16 foot transonic wind tunnels in Tullahoma, Tennessee or the CALSPAN 8 by 8 foot transonic wind tunnel in Buffalo, New York.

After determining the aircraft flowfield, the Influence Function Method (IFM) is used to determine the effect of the aircraft flowfield on the store forces and moments. NAWC-AD is recognized as an international authority on IFM[7,8,9], and has delivered the code to the Canadian Air Force and Australian Air Force, as well as NAWC-WD (Naval Air Warfare Center, Weapon Division) and United States contractors. Using the aircraft flowfield and store influence coefficients, an estimate of store aerodynamic coefficients is made everywhere in the flowfield, including carriage. The estimated store carriage loads and moments are then checked by using computational methods to calculate their value at carriage. The store aerodynamic force and moment coefficients are then input to a six-degree-of-freedom program to simulate the store's trajectory prior to the wind tunnel test. The simulated trajectories are used to help design the wind tunnel test to ensure that the most critical regions of the store separation envelope are tested. These wind tunnel tests are presently conducted at either the AEDC facility or the CALSPAN facility. These facilities have the dual sting Captive Trajectory System (CTS) capability which is required for store separation testing.

After the test has been completed, wind tunnel results are compared to the analytical predictions to ensure any discrepancies can be accounted for. The wind tunnel carriage, grid, and freestream store aerodynamic coefficients are then used to update the simulated trajectories, which should closely agree with the CTS simulated trajectory prediction. Sensitivity studies are conducted based on the wind tunnel results and the level of confidence in the data to determine the regions of the flight envelope where problems in launching or jettisoning the store might be encountered.

Finally, trajectory simulations are compared with flight test results early in the flight test program. Any discrepancy between predictions and test data can be largely attributed to differences between the assumed and actual aerodynamic moments at carriage. Therefore it is possible to determine what the carriage moments had to be in order to match the flight test results. The moments for the next point in the trajectory are then modified based on the previous results.

5. EXAMPLES

5.1 F/A-18E/JSOW

A comparison of the clean (no pylon) F/A-18C and F/A-18E aircraft flowfields was initiated to determine if the F/A-18E flowfield might cause problems in safely separating stores, compared to the F/A-18C. A PAN AIR model was developed and validated using wind tunnel pressure data measured on the wing.

The preliminary analysis indicated that the F/A-18E increased inlet area, coupled with the increased aircraft area ratio, had a significant impact on the aircraft flowfield, and might have a detrimental effect on store separation.

Prior to the January 1995 F/A-18E/F Series III wind tunnel test at AEDC, flowfield angularity predictions were made utilizing the PAN AIR model previously developed. Comparisons between test data and analytical predictions correlated very well for both the F/A-18C and F/A-18E aircraft, Figures 2 and 3. This confirmed that the PAN AIR model of the F/A-18E aircraft is a good representation and should provide good qualitative results even at low transonic speeds.

Validation of the PAN AIR model of the F/A-18E provided an opportunity to evaluate the effects of aircraft flowfield on the trajectories of stores separating from the aircraft. Since the IFM technique had been used for the F/A-18C / JSOW program, it was used again to predict JSOW trajectories from the F/A-18E aircraft. IFM assumes that there is a direct relationship between the aircraft flowfield along a store and the forces and moments induced by the aircraft flowfield on the store. Conceptually, for a store broken into N segments, this is expressed by the relationships:

$$C_N = \Sigma A_i * \varepsilon_i, \quad i=1,N$$
$$C_m = \Sigma A_i * \varepsilon_i, \quad i=1,N$$
$$C_Y = \Sigma B_i * \sigma_i, \quad i=1,N$$
$$C_n = \Sigma B_i * \sigma_i, \quad i=1,N$$

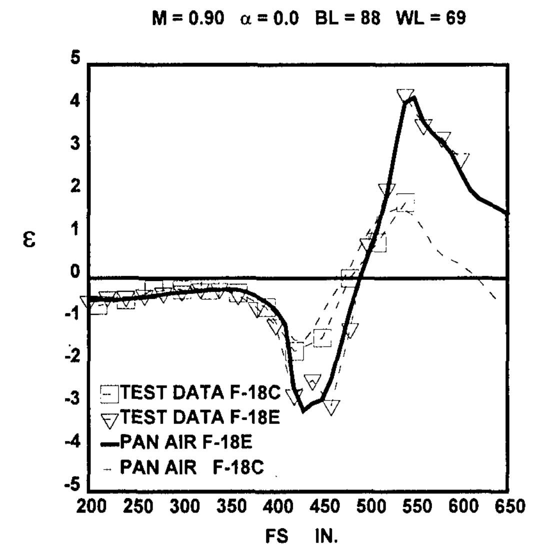


FIGURE 2: F-18 PAN AIR UPWASH PREDICTION

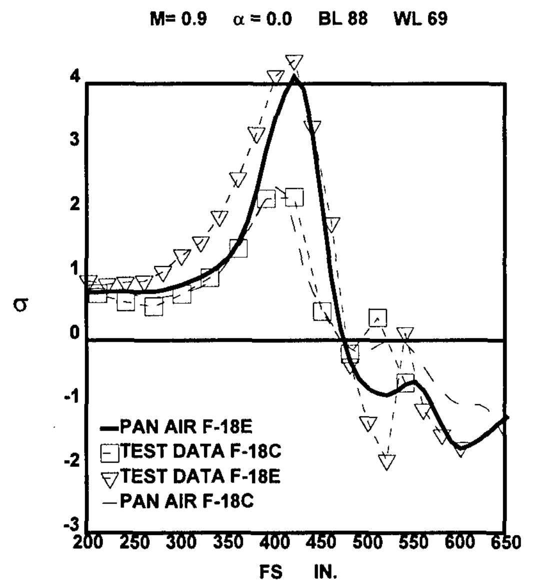


FIGURE 3: F-18 PAN AIR SIDEWASH PREDICTION

The first step in the IFM process is calibration. This entails determining the store's Influence Coefficients, A_i and B_i, which determine the store's response to the aircraft flowfield. It must be emphasized that a store's Influence Coefficients are not an aerodynamic property, but rather a solution to a regression equation relating a series of store aerodynamic loads in a known flowfield, originally obtained from experimental data. Although the IFM code provides a quick estimate of these coefficients, they cannot be used blindly. The IFM code only allows for an approximate representation of the store's geometry. The Influence Coefficients were generated for the JSOW store and were validated by comparisons with previous wind tunnel grid data.

Using the JSOW Influence Coefficients, which had been validated for the F/A-18C aircraft, along with the F/A-18C and F/A-18E flowfields, shown in Figures 2 and 3, trajectory predictions were made for the JSOW store from the F/A-18E aircraft. These trajectory predictions were compared to the equivalent trajectories from the F/A-18C aircraft. As displayed in Figures 4 and 5, the IFM predictions for the JSOW trajectories from the F/A-18E were in excellent agreement with the CTS test data for the store on the midboard station with a tank inboard, but underpredicted the yawing moment for the store on the inboard pylon. Considering the fact that the predictions were made three years prior to the wind tunnel test, it is clear that the IFM technique can give a good qualitative estimate of aircraft flowfield effects.

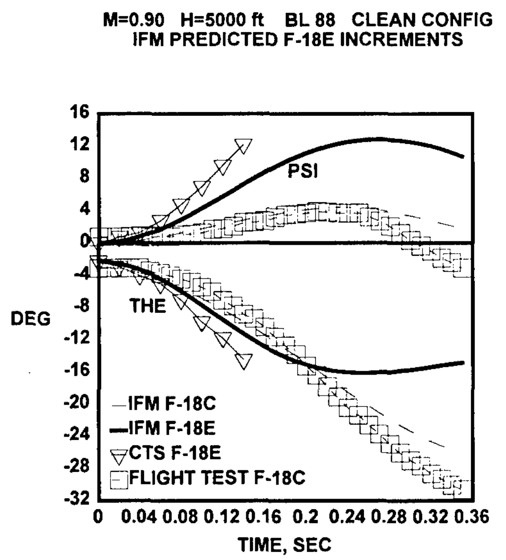


FIGURE 4: JSOW JETTISON PREDICTION

5.2 F-14/GBU-24

The approach used for the GBU-24 store differed somewhat from that for all other aircraft/store programs. In this case

the flight test results were used to determine how the wind tunnel data should be used.

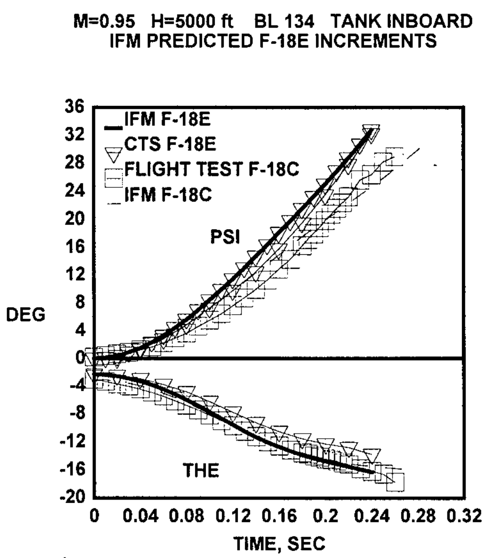


FIGURE 5: JSOW COMPARISON

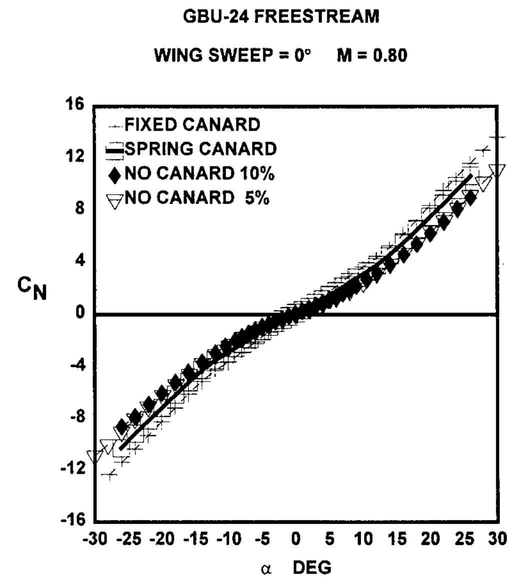


FIGURE 6: GBU-24 FREESTREAM

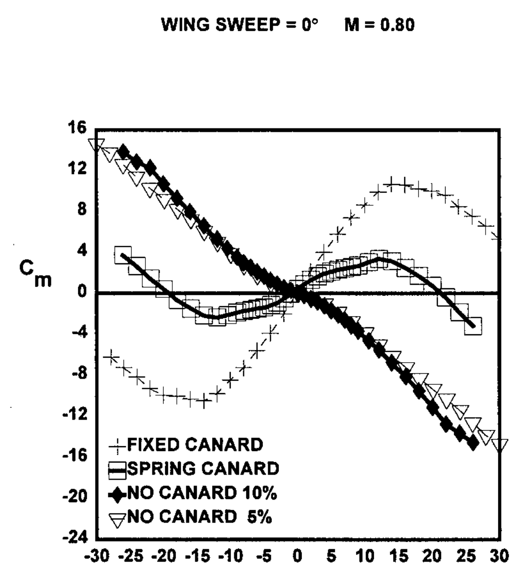


FIGURE 7: GBU-24 FREESTREAM

The GBU-24 store has two characteristics that make predicting flight test trajectories challenging. The wing of the store opens during the first 150 ms of the trajectory. It was not possible to model this wing opening sequence during the wind tunnel test trajectories. Grid data were taken for both the wings open and wings closed configurations. Furthermore, the GBU-24 canards are free floating during the initial part of the trajectory. Previous flight test data for the F-15 and F-18 aircraft have failed to match predictions based on wind tunnel data for either fixed canards (at 0^{o} deflection angle), or for the store with the canards removed. To predict flight test trajectories, particularly for the GBU-24 configuration released from the F-14 forward station (Station 3), flight test results were used to interpret the wind tunnel data.

A wind tunnel test for the F-14/GBU-24 configuration was conducted at the AEDC 4 by 4 foot transonic wind tunnel. During this test CTS grid, CTS trajectory, carriage loads, and freestream test data were taken for both the canards on and canards off configurations, with the wings both retracted and open. As depicted in Figures 6 and 7, the pitching moment changes from unstable to stable when the canards are removed. This occurs even though the normal force shows little canard effect. Test data for the free floating (spring) canards seem to fall between the canards on and off data, Figure 7. The wind tunnel test freestream and grid data were then used only to determine that, for any combination of canards on and canards off test data, a safe release point would be Station 3 at M = 0.82.

A flight test for the release of the GBU-24 from the F-14 aircraft forward station was conducted on January 23, 1996. The trajectory using the canards off freestream and grid data gave the best match to the flight test results for everything but the pitch rate, Figure 8. Since the canards on wind tunnel data indicated a sharp nose down pitch rate, while the

canards off data indicated a slight nose-up pitch, it was postulated that the reason for the disagreement in pitch results might be attributable to the aircraft flowfield effect on the undeflected canards. Since a fixed canard for this case carried a negative lift, the canard would have to deflect nose up to neutralize this effect. Once the store is released, the canard would take some time to return to it's neutral position, which would initially cause the GBU-24 to pitch nose-up. At this flight condition an excellent match with the flight test results was obtained when an increment of C_m = 2.3 was applied to the canards off grid data, Figure 9.

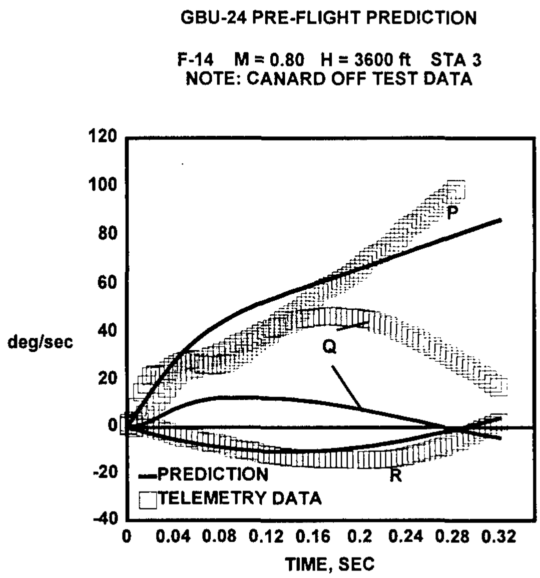


FIGURE 8: F-14/GBU-24 RATES

Upon examination of the entire flight envelope, a C_m offset coefficient ranging from 2.3 to 3.0 yielded excellent agreement with flight test data. Flight test videos for Station 3 launches showed the canard was deflected nose up in carriage. Both the trajectory results and the flight videos indicate that the response of floating canards is opposite to that indicated by wind tunnel data for fixed canards. Further flight test data will be examined to determine if these results are repeatable.

6. PRESENT AND FUTURE

Currently this process is in use on a multitude of programs. These programs include: F/A-18C/D / JDAM, F/A-18C/D / JSOW, F/A-18C/D / AIM-9X, F/A-18C/D / ASRAAM, F/A-18C/D / ITALD, F-14 / JDAM, F-14 / AIM-9X, AV-8B / JDAM, AV-8B / AMRAAM, F-4 / AQM-37, DC-130 / BQM-74, P-3 / AIMS, P-3 / XGLIDER, CF-5 / AQM-37, and CF-5 / BQM-74C. A large store separation effort is also underway on the F/A-18E/F. This work is currently in EMD where there are 32 different weapons loadings to be analyzed. After EMD, there is a Follow On Testing and Evaluation (FOT&E) program that will include JSOW, JDAM, GBU-24, SLAM-ER, and JASSM among other stores.

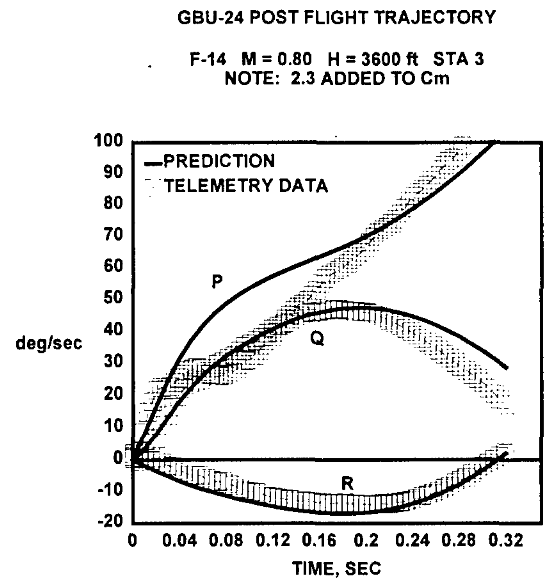


FIGURE 9: F-14/GBU-24 RATES

At NAWC-AD the nine Aerospace Engineers that comprise the Store Separation/Flight Clearance Group are responsible for the wind tunnel testing and analysis portion of these efforts. This group works closely with Flight Test Engineers to ensure that an organized, timely, cost effective, and dependable analysis is provided for each effort. Co-location is essential for this to work.

NAWC-AD is continuously developing and improving its methods and tools to meet the requirements of these present and future aircraft/store certification programs. As aircraft and weapon shapes become more complex, effective early diagnosis of aircraft flowfields is essential to successful store carriage and separation. Any successful store certification program must start with full understanding of the aircraft flowfield and its effect on the store.

Building on a solid experimental base, NAWC-AD is actively pursuing analytical developments that will enhance the store flight clearance process. It is required that these tools: are validated for complex configurations, are flexible, and provide answers in a reasonable time frame. The NAWC-AD Aerodynamics/CFD Branch is in the same division as the Store Separation/Flight Clearance Group and is examining analytical tools that complement this goal. While our final analysis will remain primarily based on

experimental results for the foreseeable future, new analytical tools will allow us to gain further knowledge into the carriage and separation of stores. This knowledge will permit better test preparation and review of contractor results.

The recent move of NAWC-AD to Patuxent River, Maryland expands the current opportunity for other organizations to use information the Store Separation/Flight Clearance Group produces. Currently, Flying Qualities, Aerodynamics, and Structures disciplines benefit directly from information gained while examining store carriage and separation, avoiding needless duplication. As previously stated, all these groups are now co-located at Patuxent River with the Flight Test Community. So, the process of further integrating analysis, wind tunnel testing, and flight testing due to both the proximity and work of the composite organizations is continuing.

NAWC-AD has actively participated in the OSD funded Applied Computational Fluid Dynamics (ACFD) investigation into analytical techniques relating to store certification. During the past year, NAWC-AD has participated in an evaluation of several CFD codes for predicting store carriage loads. Based on the results of the comparisons, the Navy determined that none of the CFD codes could provide answers that were sufficiently accurate for store separation clearance purposes. However, the Lockheed SPLITFLOW[10] code was clearly superior to the other methods examined, and should prove useful in qualitatively predicting aircraft flowfield effects at transonic speeds.

7. CONCLUSIONS

The Navy has developed an Integrated Test and Evaluation approach, combining wind tunnel testing, flight testing and computational aerodynamics, to determine the safe separation of stores from aircraft. This approach is anchored in the realization that although flight test results are the bottom line; wind tunnel testing, flight testing, and computational aerodynamics are dependent upon and essential to one another. The Integrated Teat and Evaluation approach has proven to be useful in several recent Navy store separation flight test programs, and is presently being used in the F-18E/F aircraft/store integration program.

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F/A-18E/F TRAJECTORY IMPROVEMENT STUDY

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ABSTRACT

The original F/A-18E/F configuration based on preliminary analysis predicted the existence of a major store separation problem due to a more adverse flowfield than the F/A-18C/D aircraft. Several reasons contribute to the problem which include a wider fuselage, larger wing area and thicker wing, new inlet design with more inlet spillage, and an additional pylon station on each wing. The wing pylon stations were left at there original locations relative to the aircraft centerline.

After extensive weapons separation testing and trajectory analysis in the AEDC 16T transonic wind tunnel, it was projected that the current aircraft configuration had a major separation problem and would not meet the E/F release and jettison specification requirements. Therefore, a major trajectory improvement study was undertaken to improve the release and jettison operational envelopes.

NOMENCLATURE

AEDC	Arnold Engineering Development Center, Tullahoma, TN.
BIT	Build In Test
CFA	Conical Fin Assembly
CFD	Computational Fluid Dynamics
CVER	Canted Vertical Ejection Rack
DOOR	Outside midboard/inside midboard/outside inboard/inside inboard pylon door deflection angle, deg
EMD	Engineering & Manufacturing Development Phase
FOT&E	Follow-on Operational Test and Evaluation
HIPPAG	High Pressure Pure Air Generator
MDA	McDonnell Douglas Aerospace, St Louis, MO
NAWC-AD	Naval Air Weapons Center, Patuxent River, MD
NAVAIR	Naval Air Systems Command, Patuxent River, MD
PACER	Pneumatically Actuated Constrained Ejector Rack
6-DOF	Six degree of freedom
NZ	Store release load factor, g
Miss Distance	The distance between the release store to the closest point on the aircraft or adjacent stores.
MRI	Minimum release interval, Msec
PHI	Store roll angle (+ clockwise, looking upstream), deg.
PSI	Store yaw angle (+ nose right) in aircraft axis, deg.
THA	Store pitch angle (+ nose up) in aircraft axis, deg.
Time	Trajectory time, sec.
Toe angle	Inboard/midboard/outboard pylon toe angle (+ nose rotated outboard), deg.
XA	Store longitudinal displacement (+ upstream) in aircraft axis, inches
YA	Store lateral displacement (+ toward right wing tip) in aircraft axis, inches
ZA	Store vertical displacement (+ down) in aircraft axis, inches.

INTRODUCTION

The F/A-18E/F has one of the most ambitious EMD flight test programs undertaken by any weapons integration program. The following 32 weapons loading shown in Table 1 are required to be completed by the end of the EMD program. New weapons, mixed store loadings, MRI problems, and any left over problems from EMD will be tested in an FOT&E period after completion of EMD. This will enable the aircraft to be operational with a reasonable array of weapons when the aircraft is placed in fleet service in year 2002.

After extensive weapons separation wind tunnel testing in the AEDC 16T transonic wind tunnel, with data analysis in the form of trajectories and miss distance calculations, it was projected that the current aircraft configuration had a major

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

separation problem and would not meet the F/A - 18E/F release and jettison specification requirements. Therefore, a major trajectory improvement study was undertaken to improve the release and jettison operational envelopes.

Many concepts were evaluated and screened by a subsonic panel method, and CFD to assist in selecting concepts to be wind tunnel tested. Parametric trajectory studies were generated by a 6-DOF separation program using measured GRID data from the wind tunnel tests. The following eight (8) best concepts were further evaluated in the wind tunnel as potentials to improve release and jettison characteristics of the F/A-18E/F aircraft: (1) pylon toe, (2) release sequence change, (3) pylon doors, (4) pylon trailing edge flap, (5) fuselage bumps, (6) wing spoilers, (7) pylon fences, and (8) new bomb rack with yaw restraint.

From this group the best three (3) concepts from the wind tunnel study were selected for further wind tunnel testing and trade studies by MDA and NAVAIR. Pylon toe was combined with release sequence changes, new bomb rack with yaw restraint, and pylon doors were chosen for more testing and analysis.

PYLON TOE CONCEPT

The pylon toe (Fig 1) by its self was not effective enough to provide the desired improvements. But when toe was combined with a release sequence change, the combination was effective, and chosen because it was a passive system that required the least amount of retesting and modification to the aircraft. The pylons had to be redesigned, loads testing had to be retested in the wind tunnel, and the pylon attachment points in the wing had to be modified.

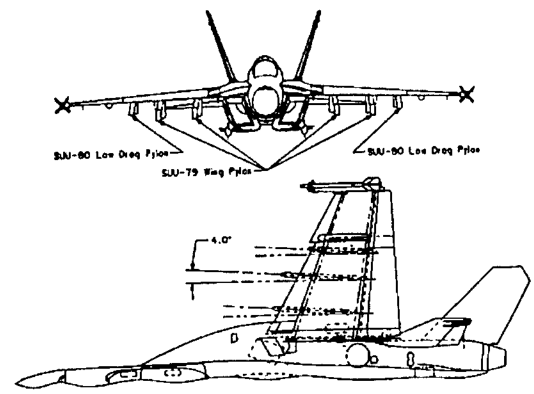


Fig 1 F/A-18E/F Pylon Toe Characteristics

- All pylons toed 4 degrees nose outboard
- Pylons toed about the front wing pylon attachment point
- Wing needed to be modified for higher loads and aft pylon to wing attachment point relocated

RELEASE SEQUENCES

Figures 2 and 3 show the original and modified release sequences. The major difference is the original release sequence released the outboard store on a multiple rack first. The modified release sequence now releases the inboard store on a multiple rack first. Wind tunnel testing showed that there were favorable trajectory effects by releasing the inboard store first.

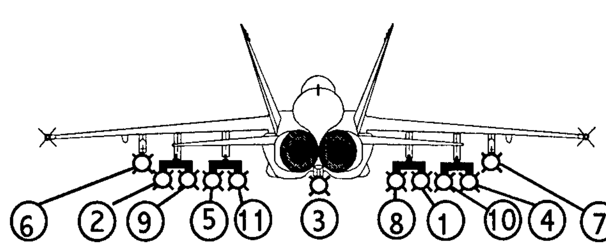


Figure 2 F/A-18E/F Original Weapons Release Sequence With CVER's

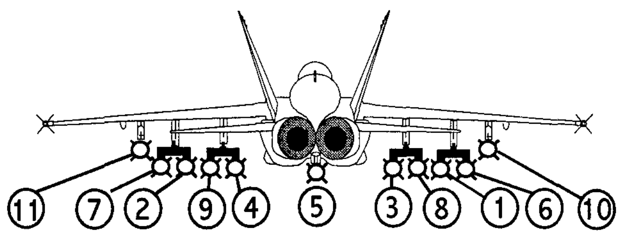


Figure 3 F/A-18E/ Modified Weapons Release Sequence With CVER's

PYLON DOOR CONCEPT

The pylon doors (Fig 4) gave the best overall improvements but required major modifications to the aircraft in order to operate. Major software would have to be modified and pylons were not thick enough to provide flush doors in the closed positions.

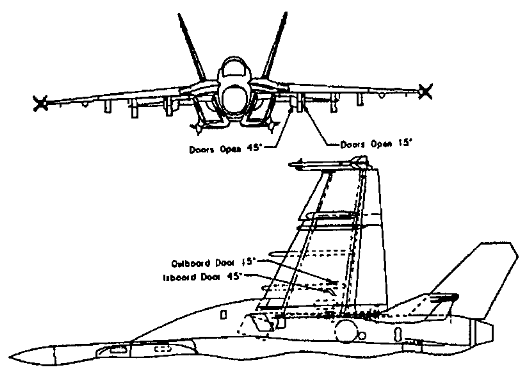


Fig 4 F/A-18E/F Pylon Toe Characteristics

- Door size (14 x 14 inches) 196 sq in area.
- Hinge sweep angle (20 degrees)
- Location (67 inches aft of forward 30 inch hook position)
- Operation (electric ball screw)
- Mounting (flush with pylon mold lines)

PACER BOMB RACK

A parent pylon mounted prototype PACER bomb rack (Fig 5) was flight tested with a MK-84 bomb on an F/A-18C/D aircraft at the NAWC-AD, and ground tested at MDA . The bomb rack made a small improvement in the release trajectories, but the improvements were not significant enough to provide the desired release envelopes.

The yaw restraint saddle could not retain the bomb from pivoting about either ejection foot whenever any pitching motion were present. The longer ejection stroke and more ejection force were not effective based on structural considerations.

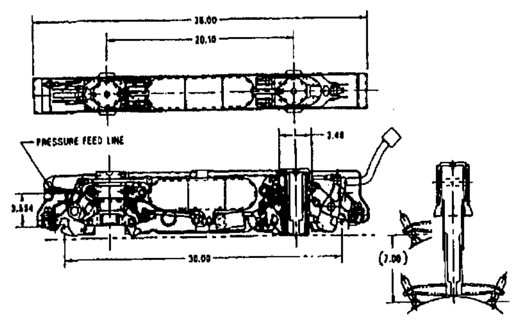


Fig 5 F/A-18E/F PACER Bomb Rack Characteristics

- Pneumatic actuated
- Increased ejection velocity when compared to BRU-32
- Increased ejection stroke (7 vs 6 inches)
- Larger swaybrace pad spacing
- Yaw restraint
- HIPPAG 5100 psi air supply for actuation
- BIT (built in test) required
- Manual swaybracing

WIND TUNNEL MODEL DESCRIPTION

A 1/10 (10%) scale high speed F/A-18E sting or strut mounted model with flow through engine ducts, manual position leading and trailing edge flaps, seven (7) external pylons with provisions for 6-component strain gage balances to measure captive carriage loads. For store separation testing, the model was strut mounted upside down in the wind tunnel with the horizontal tails removed. Removing the aircraft tails reduces the interference between the captive trajectory system (CTS) and the aircraft model, providing more flexibility in positioning the store during a trajectory or GRID sweeps. There is also a full array of stores and bomb racks available for all configurations in Table 1.

WIND TUNNEL FACILITY

All F/A-18E/F weapons separation testing has been conducted in the Arnold Engineering Development Center's (AEDC) 16T wind tunnel. Fig 6 is a picture of the F/A-18E/F model in the wind tunnel. The 16T wind tunnel is a continuous-flow, closed-loop facility capable of operation over a Mach number range from 0.2 to 1.6. The facility is equipped with a 6-degree of freedom captive trajectory system (CTS) used for positioning the store models relative to the aircraft.

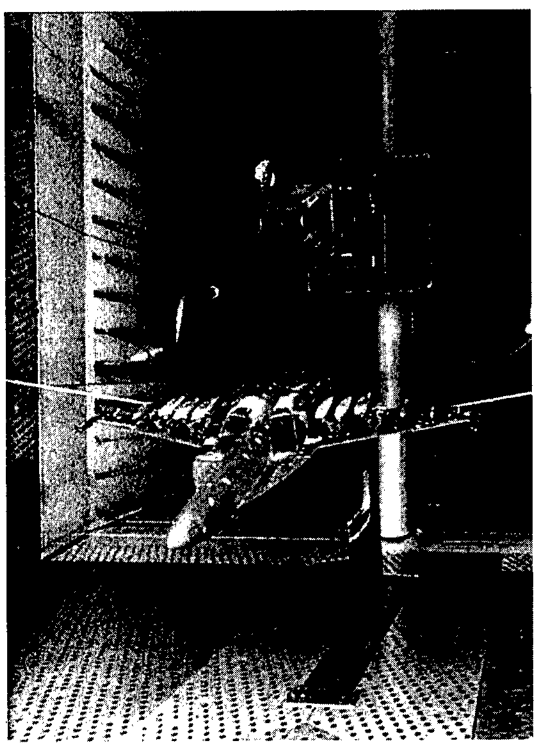


Fig 6 F/A-18E/F Model In The AEDC 16T Transonic Wind Tunnel

BEFORE STUDY RESULTS

The following presentation technique was used to convince the F/A-18E/F management and aircraft manufacture that the current aircraft design would not meet the expected release and jettison envelopes for the configurations of Table 1. Clearance envelopes were developed for each configuration in Table 1 except the AIM-9, and practice bombs (MK-76 and MK-106) which were not tested in the wind tunnel because of their small size.

Hundreds of trajectories and miss distances were calculated as a function of (aircraft loading, Mach no., altitude, NZ, and release airspeeds) to define the projected release or jettison envelopes for each configuration in Table 1 for the baseline aircraft. All trajectories were calculated using freestream and GRID data measured in the wind tunnel. This information was conducted before the aircraft were delivered to the Navy for flight tests. Up to this point, it was believed by MDA and Navy management that any weapons separation problems could be fixed during flight tests.

The following definitions are required for the miss distance plots (See Fig 7):

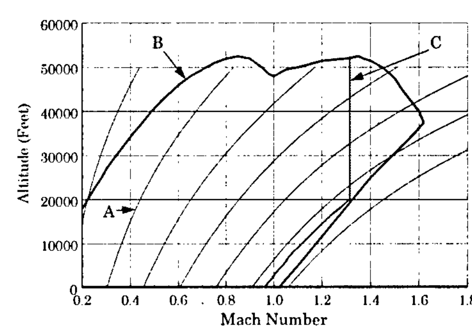


Fig 7 Miss Distance Plot Definitions

1. Lines A are constant calibrated airspeed lines (KCAS)
2. Line B is a 1G flight envelope for the aircraft.
3. Line C is one of the following:
   (a) Store limit.
   (b) Hardware limit (Launcher, bomb rack, or pylon).
   (c) Desired release limit for the store loading.
4. Color GREEN defines an envelope where the miss distance is greater than 6 inches.
5. Color YELLOW defines an envelope where the miss distance is 6 to 0 inches.
6. Color RED defines an envelope where the store would hit the aircraft, pylon, or adjacent store.

Figures 8 to 12 are examples of the projected release and jettison envelopes for some configuration of loadings from Table 1.

Figure 8 shows the jettison envelope for the 480 gallon fuel tank is YELLOW for the complete flight envelope with a projected miss distance from 6 to 0 inches. This is acceptable for the fuel tank because it has a 3-degree of freedom aft pivot that restricts most of the motion to the pitch plane and the tank is also ejected.

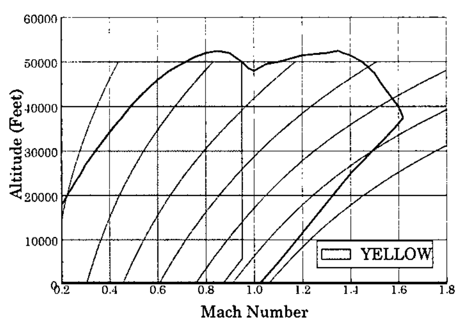


Figure 8 Projected Jettison Envelope For The 480 Gal Fuel Tank, Table 1 Loading 27

It can be seen from Fig 9 that there is a large RED area where the store is projected to hit the aircraft or adjacent store, and the YELLOW area goes from GREEN to RED in approximately 0.2 Mach number. The rate of change form GREEN to RED indicates that this store will be sensitive to small Mach number changes.

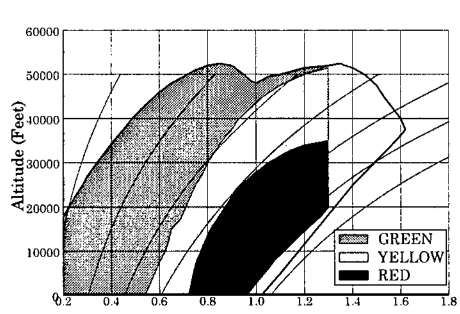


Figure 9 Projected Release Envelope For The MK-84 Mounted Next To The Fuselage, Table 1 Load 9

Fig 10 shows the same trend for the MK-84 next to a 480 gallon fuel tank as the MK-84 next to the fuselage. The GREEN area is larger, but the rate of change from GREEN to RED happens in approximately 0.10 Mach Number. Neither one of the Mk-84 predicted release envelopes is acceptable and will not meet the contract requirements.

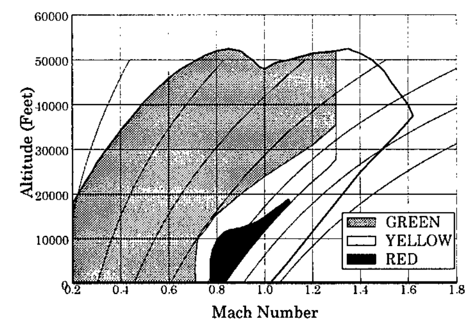


Figure 10 Projected Release Envelope For MK-84 Next To A 480 Gallon Fuel Tank, Table 1 Modified Load 9

Figures 11 and 12 show the projected release envelopes for the MK-83/BSU-85 LD stores mounted on CVER'S next to the fuselage and next to a 480 gallon fuel tank. Both of these configurations could be acceptable depending on what miss distance is acceptable, but still will not meet the contract requirements.

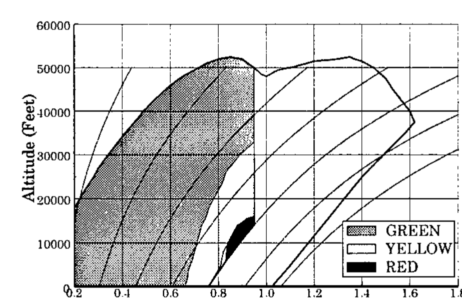


Figure 11 Projected MK-83/BSU-85LD Release Envelope Mounted On CVER's Next To The Fuselage, Table 1 Load 4

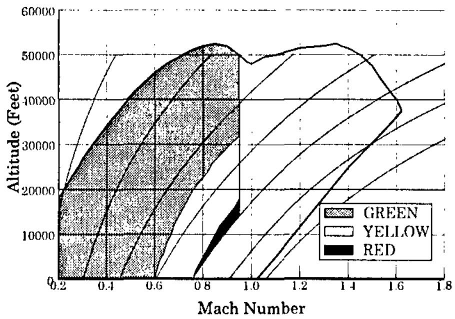


Figure 12 Proposed MK-83/BSU-85 LD Mounted On CVER'S Next To A 480 Gallon Fuel Tank, Table 1 Load 5

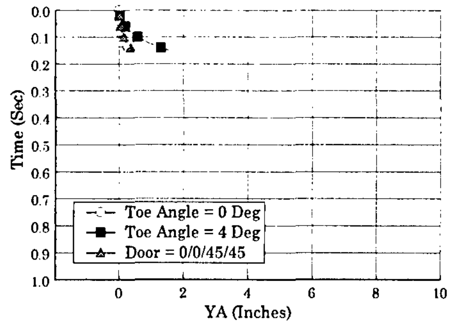


Figure 13a 480 Gallon Fuel Tank Trajectory Comparisons for Baseline Aircraft, Pylon Toe, and Pylon Doors At Mach No = 0.95, Nz = 1.0

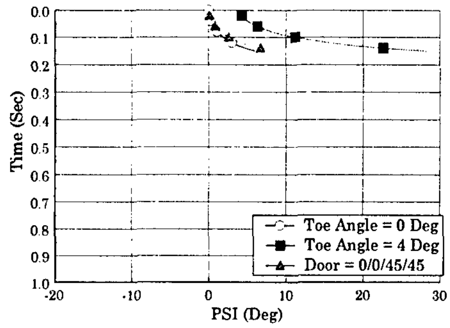


Figure 13 b Continued

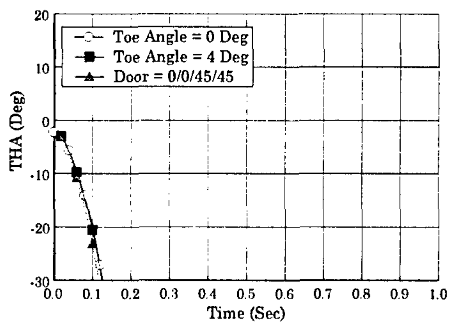


Figure 13 c Continued

AFTER STUDY RESULTS

After review of all of the separation studies, it was agreed by the Navy and MDA that the baseline aircraft would have a store separation problem and could not meet the requirements of the F/A-18E/F contract or the expectation of the fleet. Both the Navy and MDA agreed to fund additional wind tunnel testing to improve the release/jettison characteristics of the baseline aircraft. This section gives a comparison of the best three wind tunnel tested concepts and limited results. The bomb rack study will be reported at a later date because it was flight and ground tested.

Figures 13 to 16 show trajectories comparisons between the baseline aircraft with original pylons, pylon toe with alternate release sequence, and the best pylon door configuration. Only YA, PSI, THA and PHI as a function of time are presented because they show the differences between the configurations. Each configuration is presented for the critical Mach Number, normally in the Transonic range.

Figure 13 shows the trajectory comparisons between the baseline aircraft, pylon toe with alternate release sequence and the best pylon door configuration for the parent pylon mounted 480 gallon fuel tank next to dual MK-83 mounted on CVER's. Pylon doors gave the best trajectories for Mach number 0.95 at a 1 G jettison condition, but because this tank pivots the differences are not significant. At 0.1 sec the tank has pitched down to -20 degrees and has unattached from the pivot.

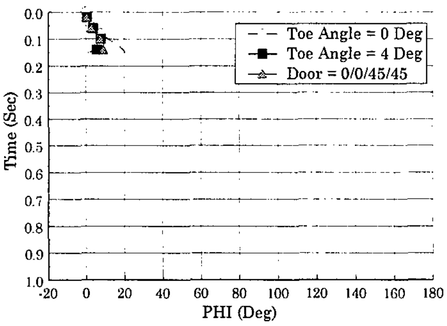


Figure 13 d Continued

Figure 14 shows the trajectory comparisons between the baseline aircraft, pylon toe with alternate release sequence and the best pylon door configuration for the parent pylon mounted MK-84 next to the fuselage. Pylon doors gave the best trajectories for Mach number 0.95 at a 1 G release condition.

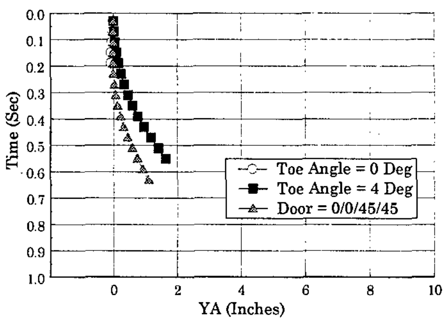


Figure 14 MK-84 Trajectory Comparisons For Baseline Aircraft, Pylon Toe, and Pylon Doors At Mach No = 0.95, Nz = 1.0

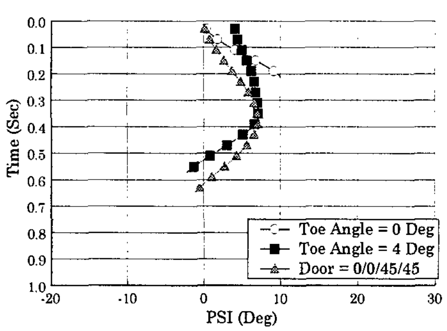


Figure 14 b Continued

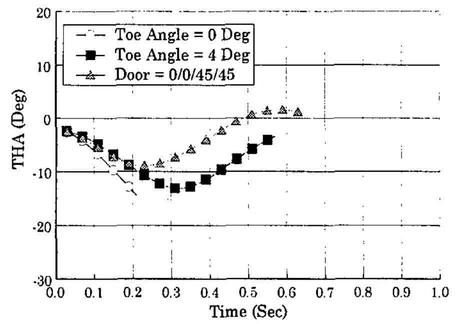


Figure 14 c Continued

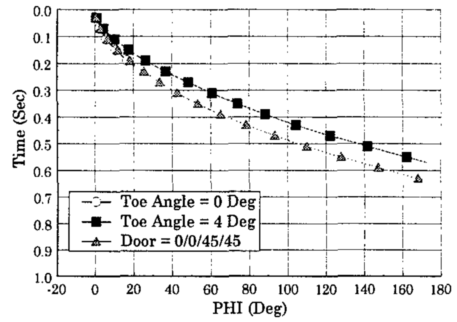


Figure 14 d

Figure 15 shows the trajectory comparisons between the baseline aircraft, pylon toe with alternate release sequence and the best pylon door configuration for the parent pylon mounted MK-84 next to a 480 gallon fuel tank. Pylon doors gave the best trajectories for Mach number 0.95 at a 1 G release condition, and eliminated the outboard Y travel for the store, and changed the sign of the store yawing-moment..

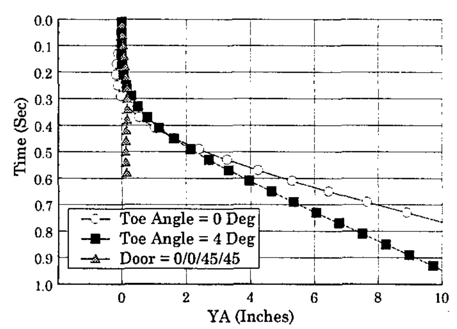


Figure 15 MK-84 Trajectory Comparisons Next To A 480 gallon tank For baseline Aircraft,

Pylon Toe, and Pylon Doors At Mach = 0.95, Nz = 1.0

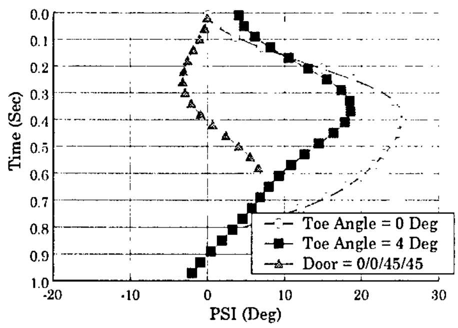


Figure 15 b Continued

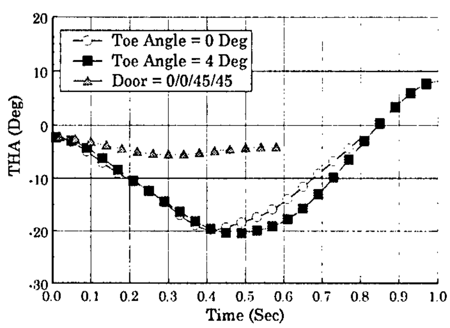


Figure 15 c Continued

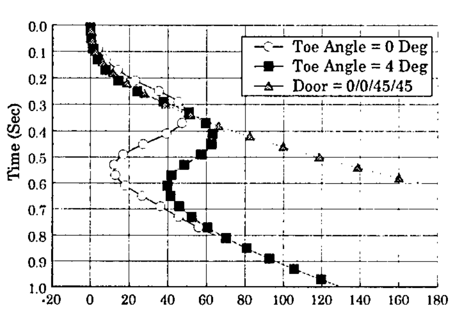


Figure 15 d Continued

Figure 16 shows the trajectory comparisons between the baseline aircraft, pylon toe with alternate release sequence and the best pylon door configuration for dual MK-83 on CVER's next to a 480 gallon fuel tank. In this case the pylon toe gave the best trajectories for Mach number 0.90 at a 1 G release condition. The CVER racks shield the effects of the pylon doors and the stores are mounted at a larger distance from the doors on CVER's. See Fig 17 for details of doors relative to stores mounted on CVER's.

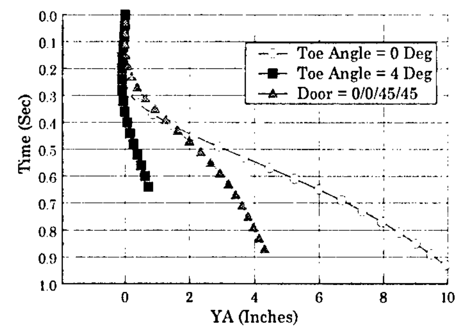


Figure 16 MK-83 next to tank

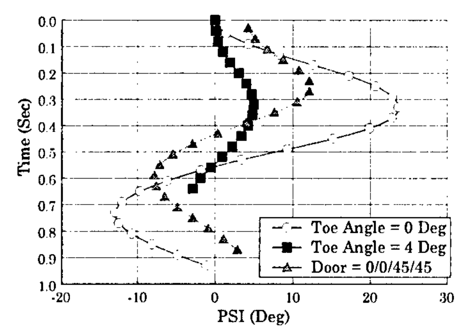


Figure 16 Continued

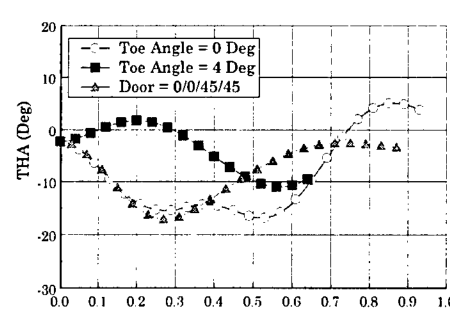


Figure 16 Continued

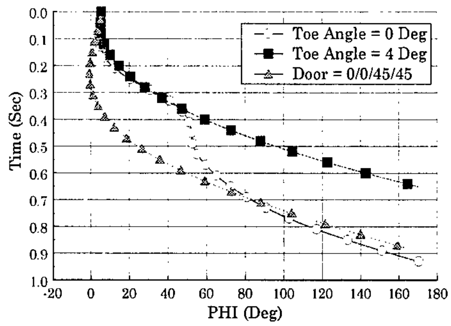


Figure 16 Continued

INSERT CVER SKETCH

Figure 18 shows the minimum miss distance comparison for the 480 gallon fuel tank jettison at several Mach numbers. Pylon doors still provided the most miss distance at all Mach numbers.

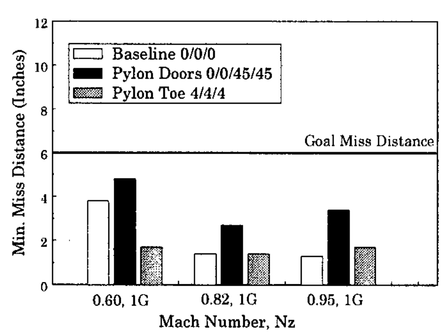


Figure 18 480 Gallon wing Tank Jettison

Figure 19 shows the minimum miss distance comparisons for a MK-84 releases mounted next to the fuselage at several Mach numbers and store release load factors. You can see at transonic Mach numbers in dive releases the differences in miss distance are small.

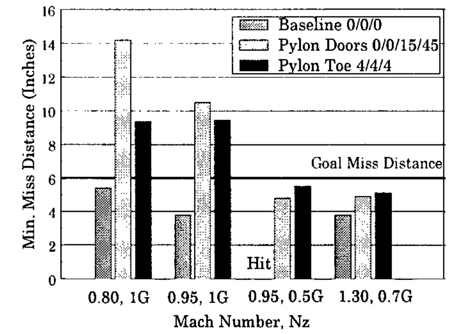


Figure 19 Mk-84 Next To Fuselage load 9

Figure 20 shows the minimum miss distance comparisons for a MK-84 releases mounted next a 480 gallon fuel tank at several Mach numbers and store release load factors. For this case either the pylon doors or pylon toe provide more miss distance than the goal. But the release load factor effect seen in Figure 19 goes away at all mach numbers.

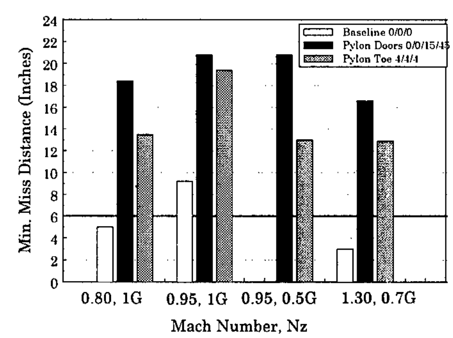


Figure 20 MK-84 Next To A 480 Gallon Tank

Figure 21 shows the minimum miss distance comparisons for dual MK-83 mounted on CVER's from station 8 at several Mach numbers and store release load factors. This figure shows that three plus inches are gained in miss distance by releasing the inboard store first from stores mounted on CVER's. The original release sequence was based on the idea that releasing the outboard stores first would reduce the asymmetric loads on the aircraft from a structures view point

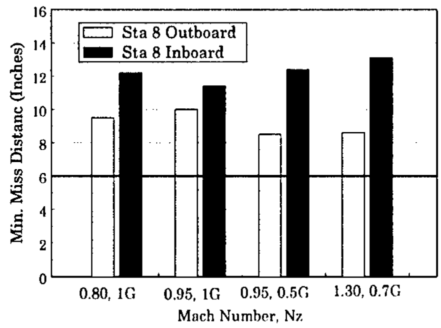


Figure 21 MK-83 on CVER's

Figure 22 shows the minimum miss distance comparisons for two fuselage stores (AIM-120 and AIM-7) mounted next to a SLAM missile released from the inboard station. The large differences in miss distance are primary a factor of static geometry. This plot should be of primary concern for FOT&E when larger fuselage stores will be tested on the fuselage such as TFLIR.

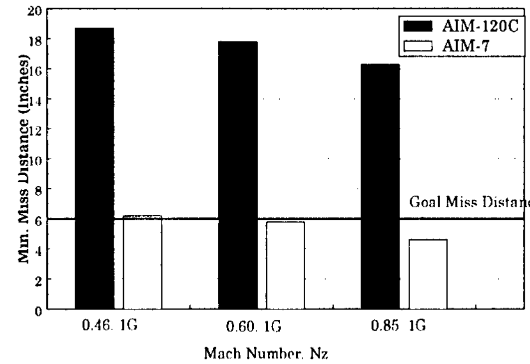
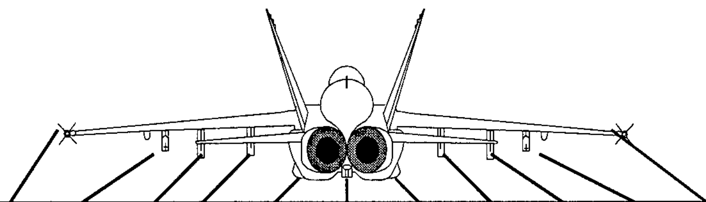


Figure 22 Effect Of Fuselage Missile On Minimum Miss Distance

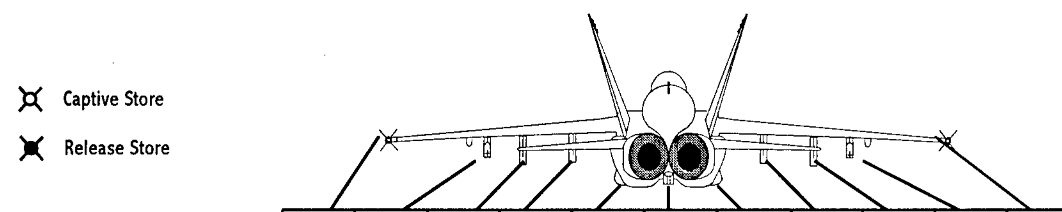
CONCLUSIONS

General conclusions are that the stores separate from the aircraft and move outboard toward the wind tips, and tails yaw toward the fuselage. Pylon doors gave the best overall improvements in the trajectories and miss distance but were unpopular with the pilots and could not be implemented on the aircraft without serious delays to the flight test program. The pylon toe with the alternate release sequence was a passive system that the Navy and MDA could live with. The major conclusion is that store separation problems should be analyzed as early as possible in the aircraft design, and not analyzed after the design is completed.



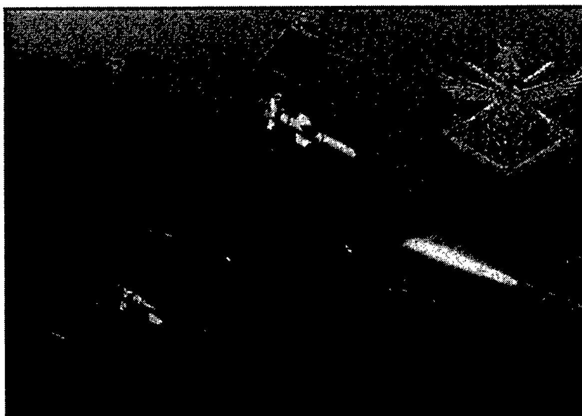
		1	2	3	4	5	6	7	8	9	10	11
1	MK-83 CFA	AIM-9	Low Drag Pylons	Low Drag Pylons	T	TGT FLIR			T	Low Drag Pylons	Low Drag Pylons	AIM-9
2	AIM-9L/M	AIM-9										AIM-9
3	MK-83 CFA	AIM-9										AIM-9
4		AIM-9										AIM-9
5		AIM-9			T				T			AIM-9
6	MK-83/BSU-85 LD	AIM-9										AIM-9
7		AIM-9			T				T			AIM-9
8	MK-83/BSU-85 HD	AIM-9			T				T			AIM-9
9	MK-84	AIM-9										AIM-9
10	CBU-99/B CBU-100/B & A/B	AIM-9										AIM-9
11		AIM-9										AIM-9
12		AIM-9			T				T			AIM-9
13	GBU-16	AIM-9			T				T			AIM-9
14	GBU-10	AIM-9			T				T			AIM-9
15	MK-76	AIM-9			T				T			AIM-9
16	MK-106	AIM-9			T				T			AIM-9

Table 1 F/A-18E/F EMD Demonstration Loadings



		1	2	3	4	5	6	7	8	9	10	11
17	AIM-120C	AIM-9	AIM-120								AIM-120	AIM-9
18		AIM-9			T	AIM-120	T	AIM-120	T			AIM-9
19	AGM-88	AIM-9	AGM-88		T				T		AGM-88	AIM-9
20		AIM-9		AGM-88						AGM-88		AIM-9
21	AGM-65E/F	AIM-9	AGM-88		T				T		AGM-88	AIM-9
22		AIM-9		AGM-88						AGM-88		AIM-9
23	WE II ER/DL	AIM-9			T				T			AIM-9
24	AGM-84D	AIM-9			T				T			AIM-9
25	AGM-84E	AIM-9			T				T			AIM-9
26	480 Gal Tank	AIM-9				AIM-7		AIM-7				AIM-9
27		AIM-9		MK-83		AIM-7		AIM-7		MK-83		AIM-9
28		AIM-9		AGM-88		AIM-7		AIM-7		AGM-88		AIM-9
29	Air Refueling Store	AIM-9				AIM-7		AIM-7				AIM-9
30	MK-82/BSU-86 LD	AIM-9				AIM-7		AIM-7				AIM-9
31		AIM-9			T				T			AIM-9
32	MK-82/BSU-86 HD	AIM-9			T				T			AIM-9

Table 1 Continued



Aircraft/Stores Compatibility - The Australian Perspective

Malcolm G. Tutty

Chief of Stores Clearance

ASCENG
ISO 9001
DQAO 0127

ADF Aircraft/Stores Compatibility Service Design Authority

Aircraft/Stores Compatibility - Australia Malcolm G. Tutty* UNCLASSIFIED

Strategic Imperatives

Population 18.5 Million

Land Mass = Continental US

No Direct Military Threat / 1998 Asian Crisis

No Significant [illegible] Obligations

UN & Multinational Forces Involvement

ADF / Air Force 50 000 / [illegible] D)

GDP $ 500 Billion

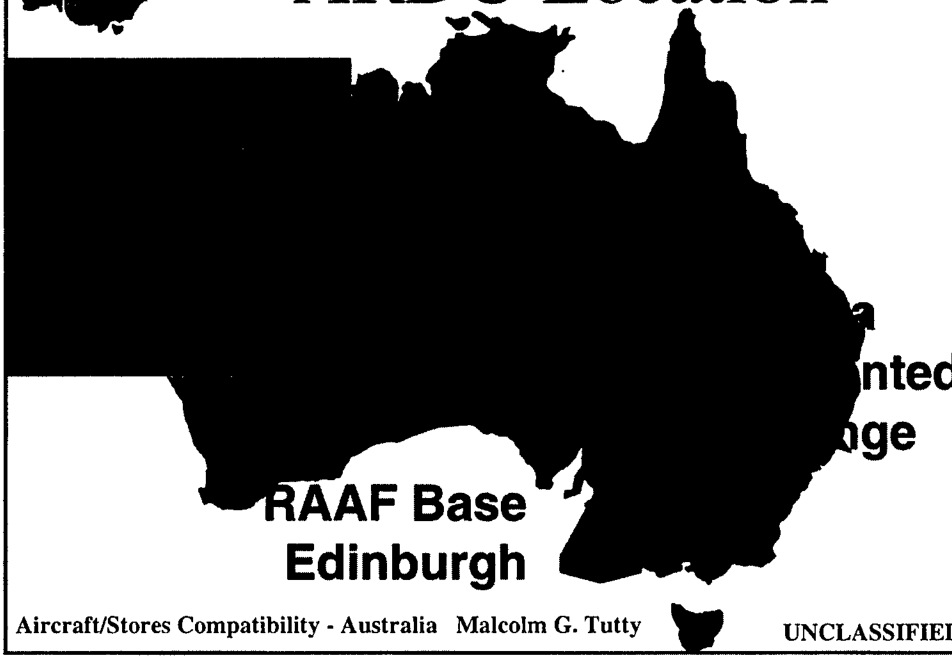
Defence Budget $ 10.5 Billion

Aircraft/Stores Compatibility - Australia Malcolm G. Tutty UNCLASSIFIED

*Mr Malcolm Tutty
Chief of Stores Clearance
Aircraft Research & Development Unit
RAAF Base
Edinburgh, South Australia S111
Australia

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

ARDU Location



Aircraft/Stores Compatibility - Australia Malcolm G. Tutty UNCLASSIFIED

Certifying Aircraft/Stores Capabilities

- **The capability provided by specified aircraft/stores configurations which are certified to be airworthy and meets approved operational suitability, effectiveness and preparedness criteria**
  - **DI(AF) OPS 1-16**

Aircraft/Stores Compatibility - Australia Malcolm G. Tutty UNCLASSIFIED

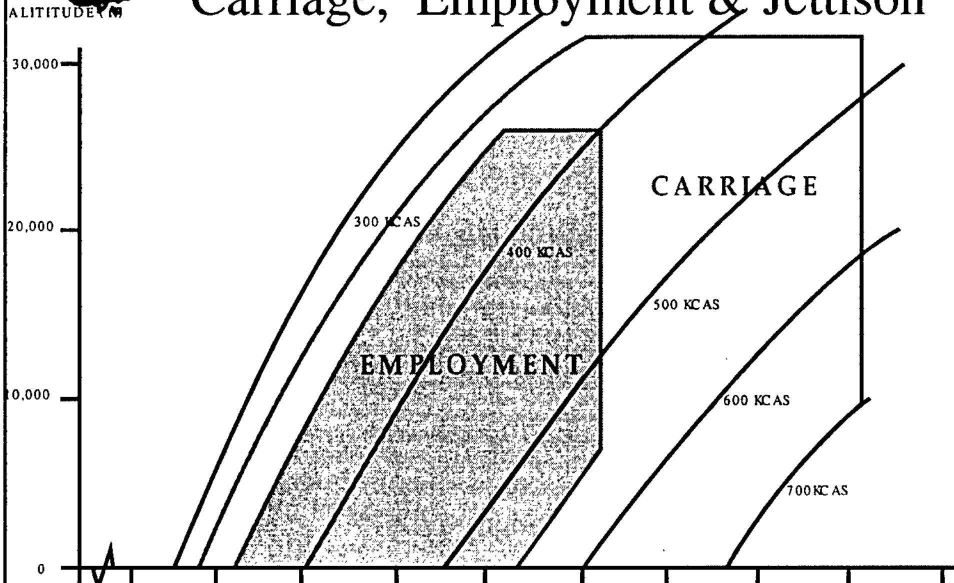
OPERATIONAL EFFECTIVENESS

- TACTICS & ROE
- THREAT
- VULNERABILITY
- DOCTRINE
- ORGANISATION
- SURVIVABILITY

OPERATIONAL SUITABILITY

- SAFETY & TRAINING
- DOCUMENTATION
- COMPATIBILITY
- INTEROPERABILITY
- AVAILABILITY
- RELIABILITY
- MAINTAINABILITY
- ROE & USAGE RATES

Operating Envelope -
Carriage, Employment & Jettison



Aircraft/Stores Compatibility - Australia Malcolm G. Tutty UNCLASSIFIED

Aircraft / Stores Compatibility

- **All aircraft/stores combinations coexist without unacceptable effects aerodynamic, structural, electrical or functional characteristics**
  - ***under all flight and ground conditions.***
    - **DI(AF) OPS 1-16 / MIL-HDBK-1763**

Aircraft/Stores Compatibility - Australia Malcolm G. Tutty UNCLASSIFIED

Aircraft / Stores Compatibility

- Aircraft/Stores Capability

OPERATIONAL REQUIREMENT

- PHYSICAL FIT & FUNCTION
- FLUTTER
- ENVIRONMENTAL & STRUCTURAL
- PERFORMANCE & HANDLING QUALITIES
- STORE EMPLOYMENT & JETTISON
- BALLISTICS & OFP VERIFICATION
- SAFE ESCAPE
- TESTING SMART
- -> OPERATING CONFIGS / LIMITS & PUBS

Aircraft/Stores Compatibility - Australia Malcolm G. Tutty UNCLASSIFIED

Aircraft / Stores Compatibility

- People, Product, Processes
- Provenance & plans
- Four Levels of Maturity & increasing risk
- Old Aircraft & Old Store
  Old Aircraft & New Store
  New Aircraft & Old Store
  New Aircraft & New Store

Aircraft/Stores Compatibility - Australia Malcolm G. Tutty UNCLASSIFIED

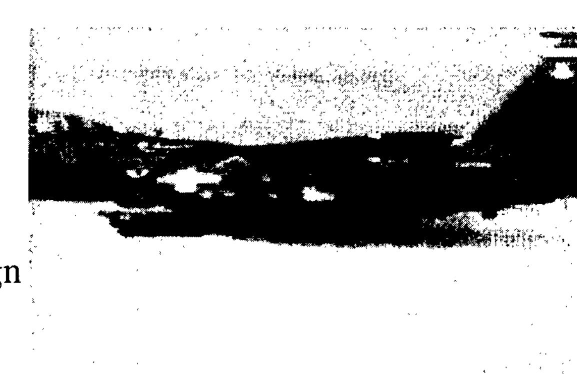
Australian Terminology

- **Aircraft/Stores Capability Operational Requirement Document (ASCORD)**
- **Store Safety & Suitability for Service (S^3)**
- **Store Engineering Data Package**
- **Aircraft EDP**
- **Aircraft/Stores Compatibility Clearance**
- **Aircraft/Stores ILS Plans**
- **Aircraft/Stores Capability Certificate**
  - **Routine in-service / T&E / Contingency**

Aircraft/Stores Compatibility - Australia Malcolm G. Tutty **UNCLASSIFIED**

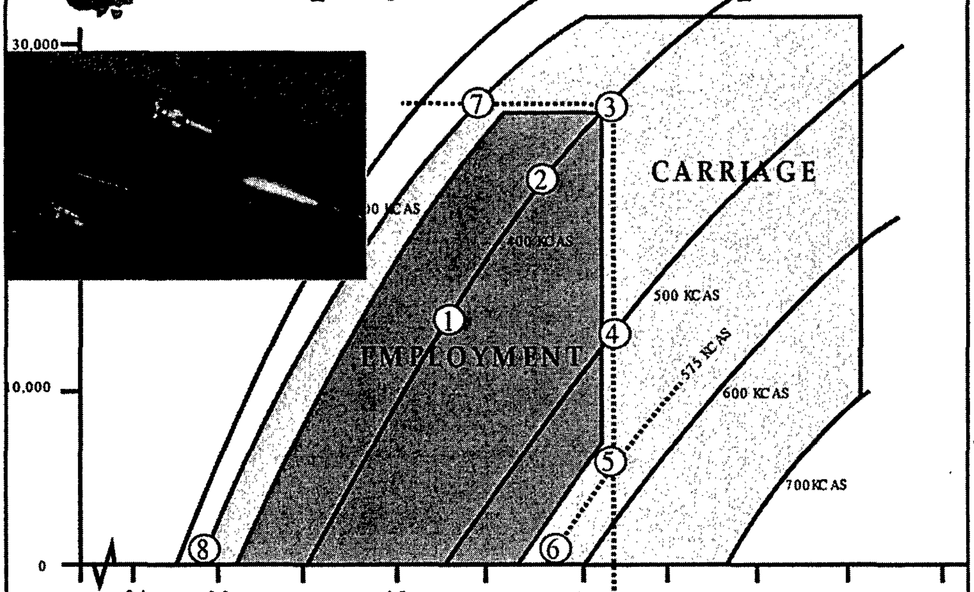
Formal ASC Training

- All Armament ASC Design Engineers, T&E & OR personnel
- 1 week Course & Practical Exercise
- ASC Policy & MIL-HDBK-1763
- 250 Aust & Foreign Graduates
- $ 120 K Upgrade
- ASC Horror Movie II



Aircraft/Stores Compatibility - Australia Malcolm G. Tutty **UNCLASSIFIED**

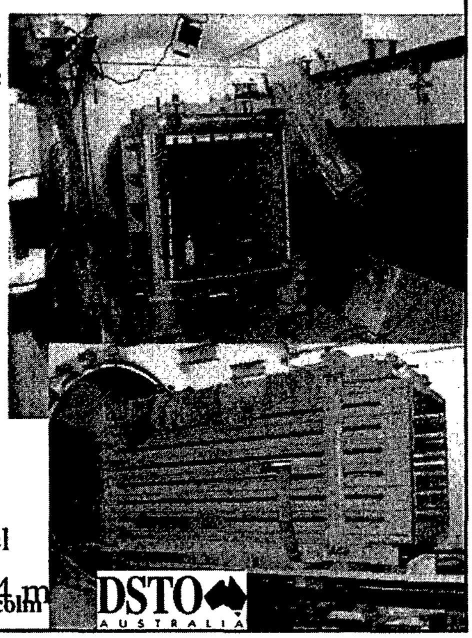
Employment Test Sequence



Aircraft/Stores Compatibility - Australia Malcolm G. Tutty UNCLASSIFIED

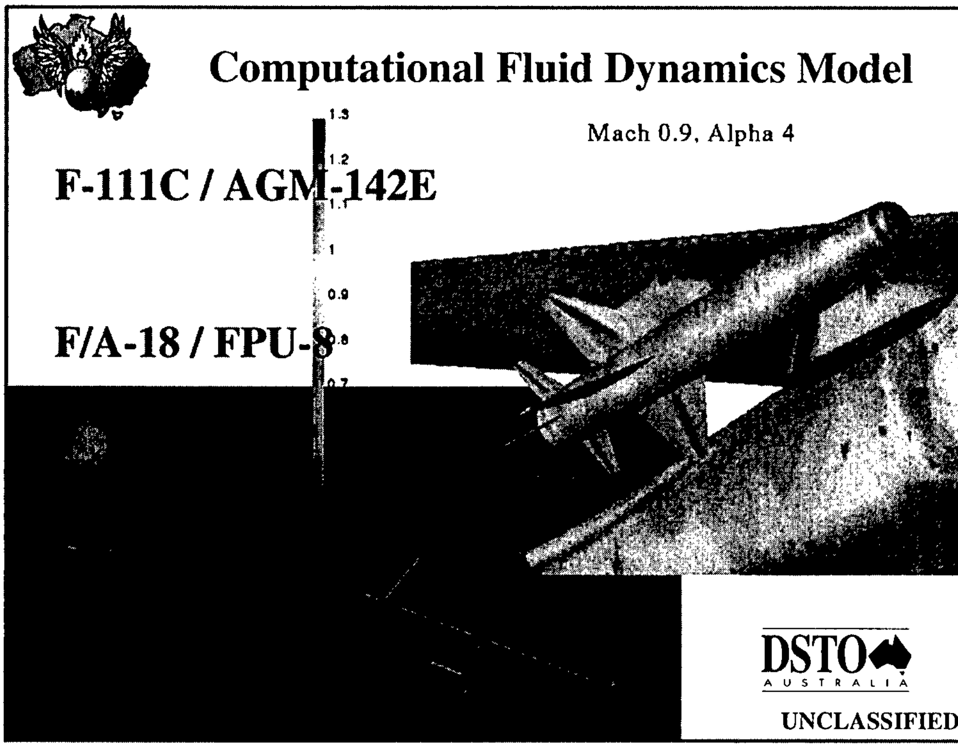
Australia's Wind Tunnels DSTO Melbourne

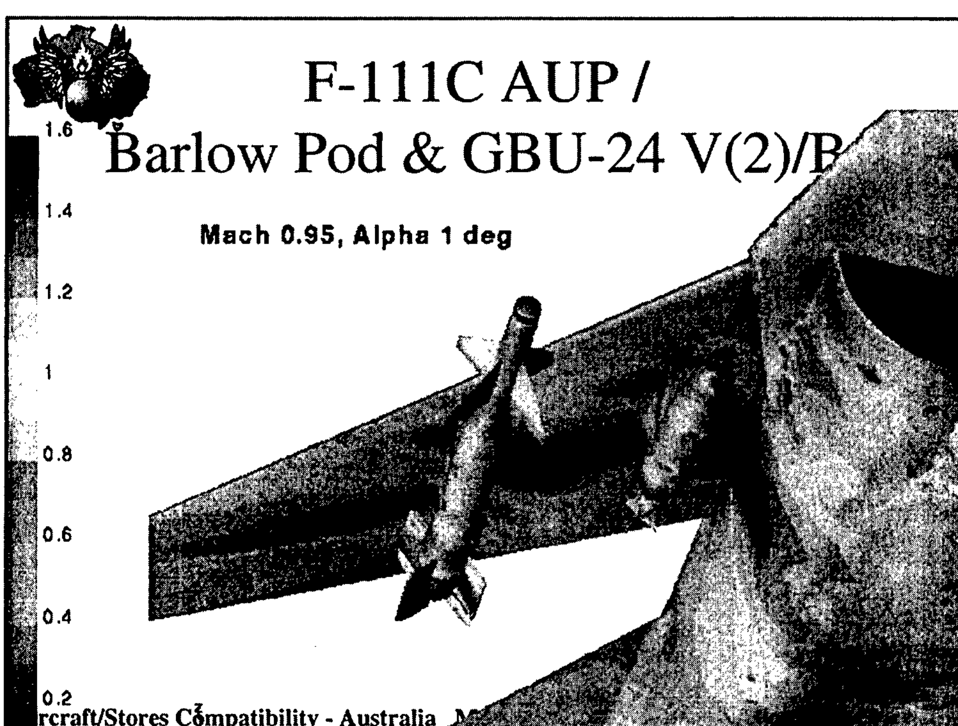
- **Transonic Tunnel Upgrade**
  - 0.8 m by 0.8 m
  - Max Mach number 1.4
  - Maxi Pressure 2 atmospheres
  - Total power 8 MW
  - Commissioning Feb 1999
- **Low-speed Tunnel**
  - 2.1 m by 2.7 m
  - 100 m/s maximum airspeed
  - Development of 1941 tunnel
- **Water Tunnel - 0.5 m by 0.4 m**



Aircraft/Stores Compatibility - Australia Malcolm

DSTO AUSTRALIA


Computational Fluid Dynamics Model
Mach 0.9, Alpha 4
F-111C / AGM-142E
F/A-18 / FPU-8
1.3
1.2
1.1
1
0.9
0.7
DSTO
AUSTRALIA
UNCLASSIFIED

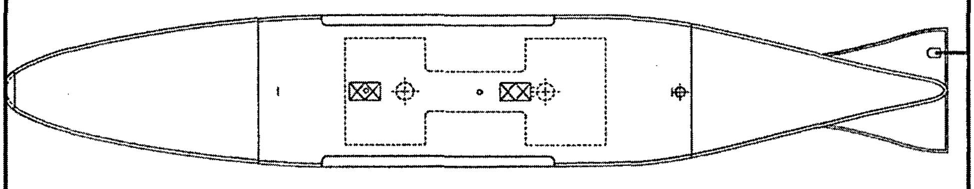

F-111C AUP /
Barlow Pod & GBU-24 V(2)/B
Mach 0.95, Alpha 1 deg
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
rcraft/Stores Compatibility - Australia

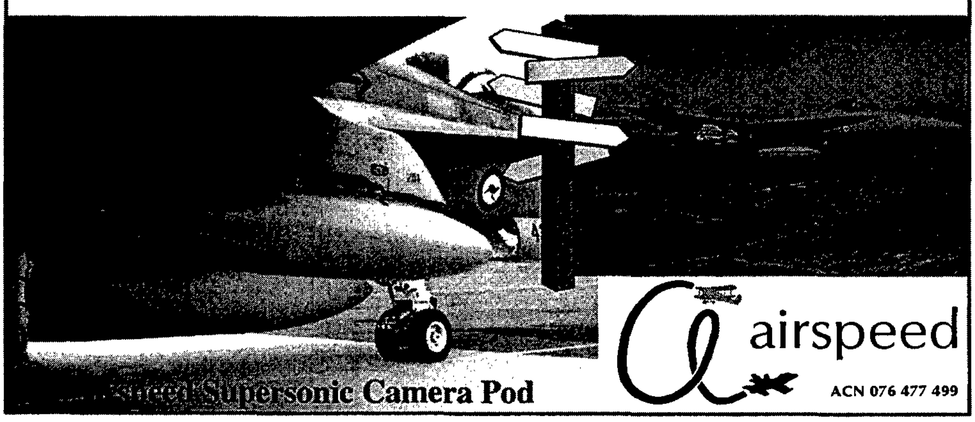
CFD CODES USED

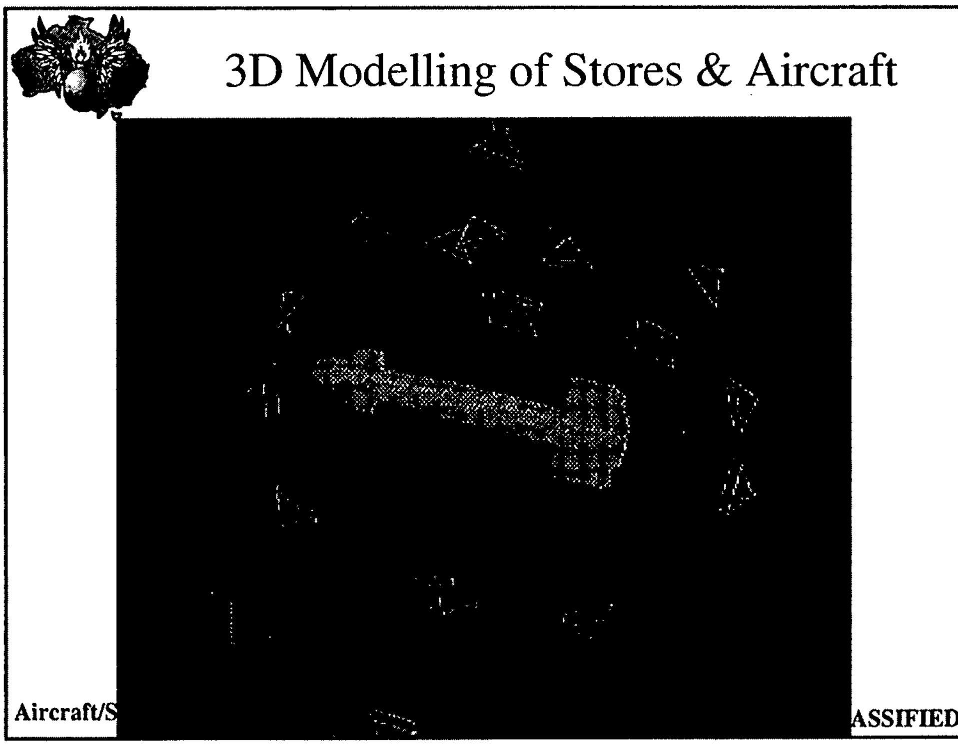
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

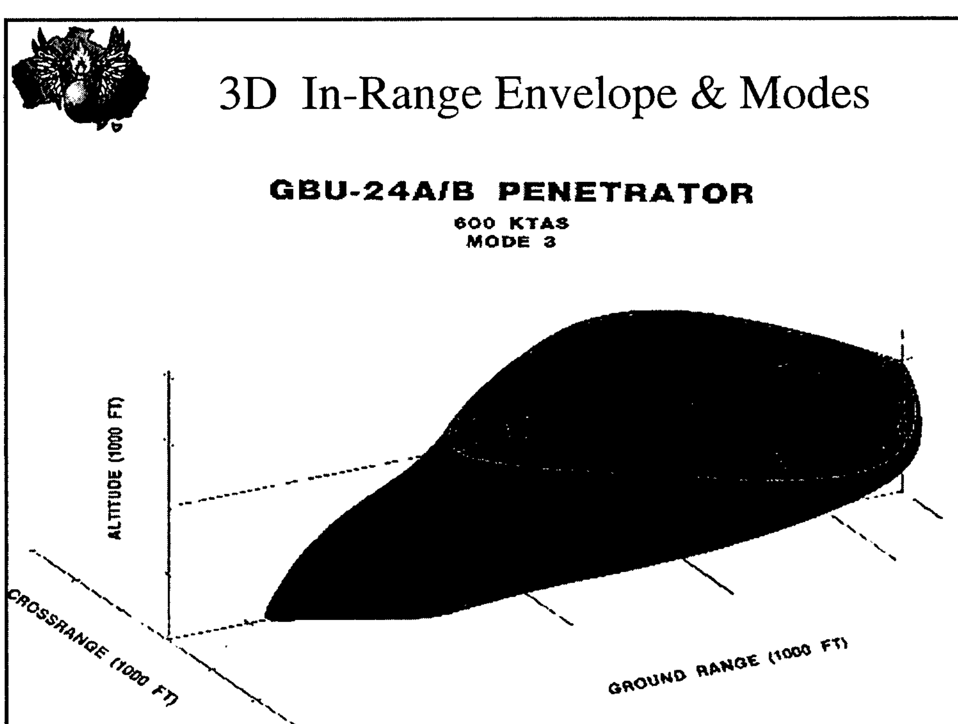
* Time required to compute the flow around a typical aircraft/store configuration
single CPU of a 16 CPU Silicon Graphics Origin 2000.

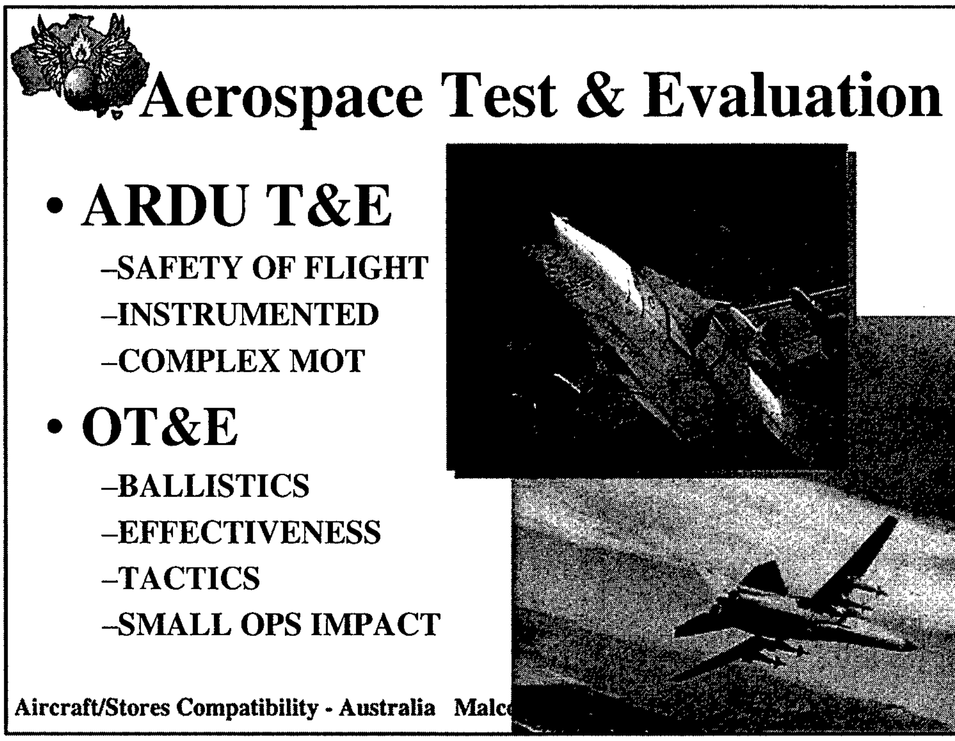
ARDU Barlow Camera Pod

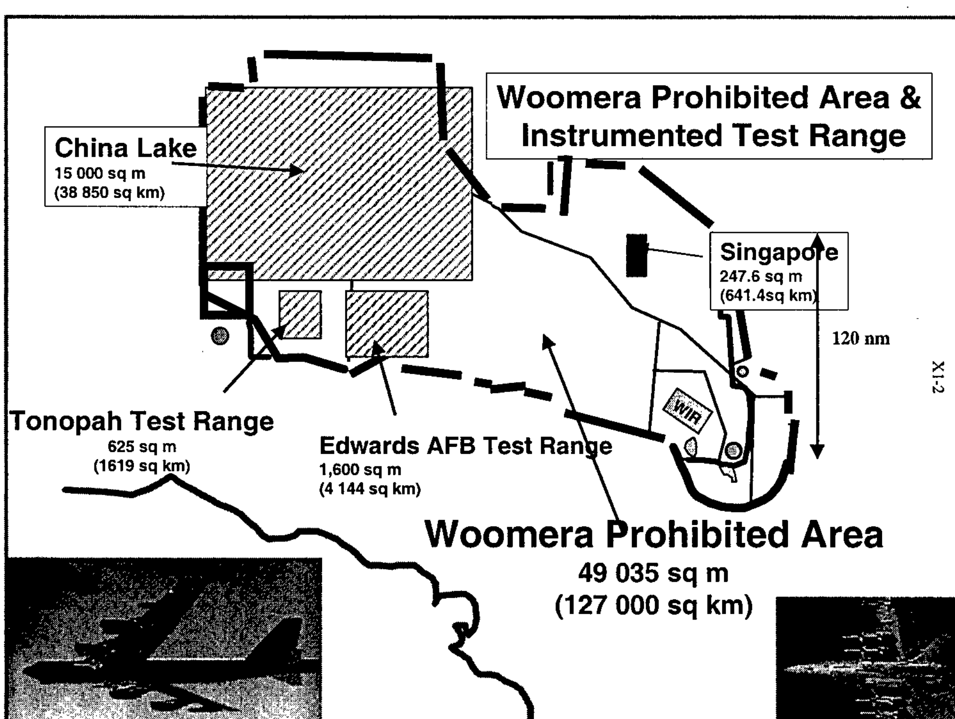





3D Modelling of Stores & Aircraft
Aircraft/S
ASSIFIED


3D In-Range Envelope & Modes
GBU-24A/B PENETRATOR
600 KTAS
MODE 3
ALTITUDE (1000 FT)
CROSSRANGE (1000 FT)
GROUND RANGE (1000 FT)


Aerospace Test & Evaluation
• ARDU T&E
–SAFETY OF FLIGHT
–INSTRUMENTED
–COMPLEX MOT
• OT&E
–BALLISTICS
–EFFECTIVENESS
–TACTICS
–SMALL OPS IMPACT
Aircraft/Stores Compatibility - Australia Malc


Woomera Prohibited Area & Instrumented Test Range
China Lake
15 000 sq m
(38 850 sq km)
Singapore
247.6 sq m
(641.4sq km)
120 nm
WIR
Tonopah Test Range
625 sq m
(1619 sq km)
Edwards AFB Test Range
1,600 sq m
(4 144 sq km)
Woomera Prohibited Area
49 035 sq m
(127 000 sq km)
X1-2

Aircraft/Stores Compatibility Lies

- 1. It's only a software change.
- 2. It's the same as a MK82 / AIM-9 / MJU-8*. * Select any one.
- 3. Only secondary structure was modified.
- 4. The Contractor / Project Office / Cleaner* says its OK.
- 5. The Army / USAF / USN * do it all the time ...
- 6. The OT&E starts today, we don't need a Clearance then...?
- 7. It's just a "one-time" flight, we don't need a ...
- 8. This Program has CAF's top priority, we don't need a ...
- 9. Of course there's stores prep and loading procedures...
- 10. I'll still respect you after the flight.

Aircraft/Stores Compatibility - Australia Malcolm G. Tutty UNCLASSIFIED

ANY QUESTIONS ?

Aircraft/Stores Compatibility - Australia Malcolm G. Tutty

WEAPON SYSTEMS INTEGRATION IN EXISTING AIRCRAFT

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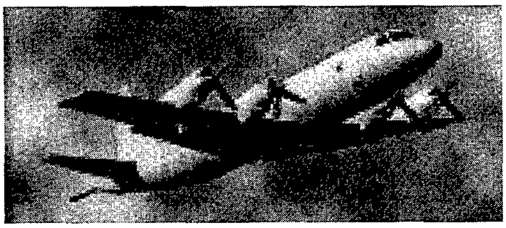
1. SUMMARY

The resurrection of an out-of-production avionics program highlights many factors that must be considered in today's era of Acquisition Reforms. Cost, Schedule, and Performance have never left the Program Manager's visual horizon, and certainly Politics has entered the picture more seriously during lean budget times. With funding continually being reduced which lowers quantities purchased, how can the Program Manager effectively integrate weapon systems in existing aircraft in a rational manner and maintain common configuration with that which already exists in the Fleet?



The P-3 Orion aircraft has existed in the U.S. Navy inventory since its inception in 1963. As a derivative of the Lockheed Electra, the P-3 has been modified multiple times to accommodate many different configurations from the original P-3A to the latest Antisurface Warfare Improvement Program avionics upgrade in the P-3C Update III. The airframe's fatigue life allows the P-3C to remain in existence beyond the year 2015, given a potential Service Life Extension Program. Consequently, weapon system improvements must be incorporated into existing platforms in order to meet emerging Fleet requirements.

The P-3C conducts all facets of the surveillance mission including anti-submarine warfare, anti-surface warfare, mining and intelligence. New functional capabilities are being added to the U.S. Navy P-3C inventory for torpedoes, air-to-surface launched weapons, tactical decision aids, communications, and sensors. It is necessary to consider multiple factors required to implement these capabilities in a cost-effective way. Options include use of state-of-the-art, Commercial-Off-The-Shelf (COTS) or Non-Developmental Items (NDIs) avionics integration with the existing, and sometimes technically obsolete, avionics on the airplane.

This paper addresses the primary factors that allow the acquisition process to purchase an effective retrofit kit that meets evolving U.S. Navy's P-3 Fleet requirements, using my personal experiences in the weapon systems integration and modification of existing P-3C aircraft. These factors are analogous to any aircraft modification encompassing weapons integration. Contributing factors include procurement policies, analog versus digital interfaces, man-machine interface, and testing. The pros and cons associated with the use of non-military standards, COTS, or NDI in a cost-effective way will also be exemplified using the P-3C Update III Block Modification Upgrade Program (BMUP) that the U.S. Navy's Maritime Surveillance Aircraft Program Office is executing.

2. BACKGROUND

2.1 P-3 History

As outlined in Janes "All the World Aircraft, " the P-3 has had many derivatives and configurations both in the U.S. Navy and internationally. Existing U.S. Navy assets of 241 aircraft include the P-3C Non-Update, Update I, Update II, Update II.5, Update III, and recently the P-3C Update III with the Anti-surface Improvement Program (AIP) retrofit kit. As well, many of these series of P-3C's have multiple avionics and sensors configurations to support evolving specific missions including Counter Drug, Beartrap, and Special missions. Also, the EP-3E aircraft conducts electronic intelligence gathering. Maintaining configuration management of these multiple type/model/series to support maintainability and logistics has been a challenge, but is manageable given intense coordination among the acquisition managers, fleet commanders, and industry.

2.2 Life Of The P-3 Airframe

With the change in national interests between the 1980's to the 1990's came a shift of Department of Defense budget trends. Decreasing dollars equate to a different focus on how to address the continuing desires for freedom of the seas. Subsequently, changes in requirements have forced a restructuring and replanning of the existing P-3C airframes' life expectancy. The U.S. Navy's Structural Appraisal of Fatigue Life Affects (SAFE) coupled with the original engineering manufacturer, Lockheed Martin Aeronautical Systems (LMAS), Burbank, California allowed a 38.5 year service life for the airframe. However, the airframes are exhibiting less operational life than service life. The Sustained Readiness Program (SRP) corrects these deficient airframe components and recoups the operational life to the service life of 38.5 years. In addition, the U.S. Navy is examining through a Service Life Assessment Program (SLAP) to measure and confirm on an existing fleet P-3C the structural integrity after SRP corrections. This data will be used to support a potential Service Life Extension Program (SLEP). The intent is to identify those airframe components that will allow the P-3C airframe to structurally remain in operation until the year 2015 and beyond. Beginning in 1998, requirement studies are being conducted towards a replacement for the P-3C. These studies for a Maritime Multi-mission Aircraft (MMA) are being conducted by the U.S. with international participation.

Consequently, weapon systems upgrades to the P-3C to support emerging warfighting capabilities will continue for some years, given new technological advances.

2.3 Block Modification Upgrade Program

In the U.S. publication "Commerce Business Daily" of February 15, 1997, was the following:

"The Naval Air Systems Command intends to award a cost plus fixed-fee contract for NRE/NRSU with four production options for kit production on a Firm Fixed Priced basis to Lockheed Martin Tactical Defense Systems for the P-3C Update III Block Upgrade. This contract will procure 25 kits. These upgrade kits are to be installed into P-3C Update II and II.5 aircraft for the U.S. Navy with potential for foreign military purchase." (1)

The P-3C Update III program was initiated in 1984 and ceased in 1991 to produce and/or retrofit 101 of the 241 P-3C airframes. The modification primarily was to replace an aging acoustic sensor and display processor and improve the environmental cooling capabilities for the aircraft avionics. However, the P-3 Fleet still requires improvement to the capabilities, readiness, and training for the remaining 140 non-Update III aircraft. Since 1991, multiple Engineering Change Proposals have been added to the existing Update III aircraft that result in a new acquisition modification program that began in 1997 considering a 'block modification upgrade'. These include: the initial Update III acoustic processor subsystem comprised of multiple computers and displays which are being upgraded

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

under a separate program to correct operational deficiencies; a new mission computer from the original P-3C avionics suite to improve reliability; an old mission tape loader; sonobouy receivers; very old tape recorders; on-line AN/AGM-84 Harpoon missile and MK-50 torpedo capabilities. Thus, the P-3C Update III Block Modification Upgrade Program (BMUP) was formed.

3. PROCUREMENT

As new requirements evolve for the maritime patrol mission, acquisition managers face the challenge of developing the plans and strategies to answer these needs. Development of these procurement strategies must consider many facets, including policies that have been directed. For U.S. Department of Defense (DoD) acquisition managers, DOD Instruction 5000 series describe the policies and procedures for "a disciplined management approach for acquiring systems and materiel to satisfy valid military needs." The intent of these directives is to "... define an acquisition environment that makes the DoD the smartest, most responsive buyer of the best goods and services, that meet our warfighters' needs, at the best dollar value over the life of the product." (2)

This same philosophy should exist for any military product purchased, whether by the U.S. or international consumers. As such, new approaches have been undertaken through acquisition streamlining and acquisition reform.

For BMUP, the acquisition strategy and plan were approved by the Milestone Decision Authority (MDA) consisting of a sole source procurement with the original prime contractor. This decision took place after a request to industry was made in the Commerce Business Daily in October 1996 to respond with inputs on how they would approach this restart. During this period of dialogue, many potential industry participants came forward. They had some very good ideas and provided some insight that otherwise would have not been considered. Due to the requirement for maintaining logistics commonality to existing P-3 programs, industry and the government recognized the need to remain with the original Update III prime contractor. However, alternatives existed with potential subsystem/subcomponent suppliers, which industry stated had some latitude for competition. In addition, the initial Integrated Product Team (IPT) had been formed to consider the government's thoughts and concerns and made a recommendation to the MDA. The IPT's thoughts supported what industry was stating. By the way, what is an IPT, and what acquisition reforms have taken place that provide better contractor-government dialogue to deliver a product to the Fleet?

3.1 Integrated Product Team

No procurement can exist without individuals with different expertise all working together to develop an end product. No one individual can tackle the myriad of problems that are faced, unless you are buying a piece of gum; and, if that piece is in a pack to be used by many people, each will "require" their own taste anyway! The Integrated Product Team (IPT) is a must. IPT members represent those competency areas of program management, systems engineering (and their subordinate specialties), logistics, reliability and maintainability, testing, training, budget analysis, contracts, and a legal counsel. IPT membership should be a cohesive group of government and industry partners. Without this bond, breakdown in communication and differing interests of the two parties can become a chasm. Thus, the IPT structure in the beginning of the procurement will evolve over the time of the weapon systems purchase. Members will move in and out depending on the needs of the IPT.

For BMUP, the initial IPT consisted of a small select group of "Grey Beards" (those who had more than 8 years of acquisition experience) representing pertinent competencies. Using some Total Quality Management techniques, the IPT ventured into the 'maze.' The engineers salivated while the trainer and logistics representatives cringed. The issues associated with the acquisition became very apparent during the dialogue, sometimes opposing, between the IPT members. However, these issues were resolved and a viable acquisition strategy formed. After the BMUP Acquisition Strategy and Plan were approved, the IPT evolved with a new group of people who took on the next phase of the task at hand. They were subordinates to the Grey Beards within the various competencies, but now were charged with executing the plan. These folks still interface with the Grey Beards from time to time, building their own experience and gaining the benefits and wisdom from their elders. As well, since the plan was to execute this program in two phases involving the prime contractor, a contract was established that allowed the prime to participate in the IPT. The first phase of BMUP had the government charged with writing the functional specifications and Statement of Work, but with contractor participation. This proved to be an extremely positive experience. The insights between the two parties -- allowing each other to dialogue real time, expressing their perspectives on the approach -- allowed a superb specification and SOW to be written. With the remaining period of Phase I, the prime contractor took these subsystem functional specifications and began the proposal process for subsystem component competitions. A unique approach that occurred was that the contractor allowed the government to participate as a voting member in the contractor's source selection process and on its committee. Specifically, I was a member of the Contractor's Source Selection Committee, and other government IPT members were part of the four subsystem competitions that occurred. Each of these 'teams' consisted of IPT members. In all cases during these competitions, the contractor had the majority of votes in all committees and teams, but the early insight gained between industry and the government was traded back and forth which provided strong cohesive answers to the tasks. The Source Selection Authority was strictly the contractor; but due to the government participation, we influenced the information provided to the decision makers. The results of the Phase I effort formed the basis of the Phase II contract for the execution of the modification and production of the subsystem components into the BMUP avionics system. The IPT was now evolving into a new phase of membership.

3.2 Simulation Based Acquisition

Simulation Based Acquisition (SBA) is a relatively new approach to the procurement of weapon systems. The Undersecretary of Defense for Acquisition and Technology stated "I support the recent emphasis on the greater use of modeling and simulation (M&S) technology to improve our acquisition programs."(3) The examples given at the National Defense Industry Association Conference for Simulation Based Acquisition were primarily the U.S. Joint Strike Fighter (JSF) and the U.S. Navy's New Attack Submarine (NSSN) program, both 'new start' programs. (4) These programs used computer simulation to aid in the process of early identification of conflicting systems requirements and engineering issues. Both programs were well funded early in the procurement, which is needed to properly use SBA. By doing SBA, they were able to trade off requirements versus design to cost-effectively establish the basis for the procurement. These programs were able to refine the requirements for not only the capabilities versus affordability, but also the potential weapon systems integration architecture variables to meet these capabilities, as the overall architecture can be a major avionics cost driver in the disciplines of cooling, power, vibration, and reliability. This approach made known those high risk areas, allowing the program managers and requirements sponsors to adjust their key performance criteria to meet an affordable approach.

However, when integrating weapons systems in existing aircraft during austere budget times, program managers do not always have the luxury to use SBA. By not doing SBA, the level of risk increases and risk management becomes more intense. One could argue that SBA should be used in all procurements. I believe that a trade-off must be determined before the program begins by the IPT to decide if the level of risk, depending on the item being purchased, is acceptable. Also, SBA requires many different items of data. With existing platforms, the simulation models from previous procurements may not exist, nor does ownership of the models by the government exist. Many times the contractor develops simulation at his expense without the government purchasing it due to funding limitations. Questions that must be answered include: Can you afford SBA with the funding given for the program? For modifying existing programs, does the funding exist to develop those simulation tools? Should the funding be increased to provide those tools for the future modifications of the airframe or weapon system? Does out-year funding exist to purchase that M&S software from the contractor at a later date? Can the simulation be used later for trainers? Does funding exist in the out-years to maintain the model?

In P-3C modification programs, funding does not exist to undertake the SBA approach. However, updated modeling of the structural integrity for the P-3 airframe will be done in the SLAP program. After that point, each modification program may be able to take advantage of this model, dependent on the fidelity and complexity of the model and how it would be applied for that particular product.

There are other roles for Modeling and Simulation that are more broad-based and used in the all regimes of testing. These will be addressed later.

For BMUP, the program was a basic restart with no new functional capabilities required. Funding was very limited. The functional requirements were well known. The risk for purchasing items with little or no development was low. Thus, the acquisition situation did not justify the use of SBA.

3.3 Politics

Industry is hungry. Due to decreasing dollars, everyone is fighting to take control of the domain. U.S. Congressional interests and inquiries never go away. This fact becomes hard and time-consuming for the Program Manager. For U.S. government acquisitions, the Federal Acquisition Regulations are used to provide policy and law in the preparation and execution of the acquisition plan. The Competition Act of 1984 is very specific in directing competition when appropriate. In the end of considering many factors affecting the procurement and integration of a desired item, the Program Manager must take a stand and execute the plan. The IPT worked very hard at addressing the issues and developing the acquisition plan that considered political factors (how many systems and from what constituency?).

For BMUP, the Program Manager was faced with many desires to satisfy specific industry partners who asked for help from their political supporters. Many point papers to answer specific questions were written. This was very time consuming and took a lot of the Program Manager's daily effort. However, the IPT's preparation and efforts supported the effective answers, resulting in the acquisition plan not being modified.

4. TECHNICAL

4.1 Commercial-Off-The-Shelf (COTS) and Non-Developmental Items (NDI)

Technological advances for the commercial market have allowed military users to consider commercial products vice those developed solely for the military. The voguish use of COTS and NDI has become increasingly popular and mandated, when appropriate, over the use of Military Standards (MIL-STDs) and Military Specifications (MIL-SPECs). This approach does not come without other issues.

R. Rosenburg eloquently wrote in his "Lessons Learned Using COTS in Real-Time Embedded Systems," "Historically there were sound reasons not to use COTS. Today technology has evolved and many of the historical problems have been overcome."(5, pg 1) Furthermore, Rosenburg states many of the issues that face engineers and program managers, and lessons learned when addressing the use of COTS in the life cycle of the program.

These include:

- Methods used to reduce the risk of initial COTS development
- COTS system design, including both software and hardware
- Modifying what should be expected at Design Reviews
- Methods to Control the Life Cycle Cost Impact
- Leveraging off of other programs (or, commonality)
- Handling Life Time Buys when the commercial
- Monitoring ongoing trends

I agree with his statement, "The systems development and its life cycle development are not independent. Part of the development must be the selection of a life cycle approach. Each system's design needs to be evaluated for development costs and risk and also needs to trade-off those concerns with life cycle cost and risk issues." (5, pg. 24)

The programs I have been associated with that use COTS-based systems have faced all the concerns that Rosenburg mentions. Other issues also include:

- Open systems architecture
  - How is the term 'Open Systems' defined?
    - At what level?
- Who will maintain the software life cycle?
  - Is there a future software "house" required?
  - Will it be the prime contractor, or organic capability?
  - What operating system is the basis for the system applications?
- Who will maintain the hardware?
  - What is the level of maintenance required?
  - Will commercial or organic depot repair facilities be used?
- Ruggedization of Hardware
  - Should environmental testing be required? If so, how much?
  - What level of environmental qualification is required?
  - What level of reliability testing is required in the proper environment?
  - Can the system/subsystem be designed around the COTS, or should the COTS be modified?

These issues are extremely important when addressing the acquisition strategy because of the information that industry needs in order to make their decisions when answering a request for proposal. Industry's bid will be determined by answers to these issues and many other factors. They will be interested in their initial and future plans to match their investments with the expected timeframe of a return on their investment, and what anticipated profit margin can be expected. These desires are coupled with their ability to meet the customers' (that is, the Warfighter and the program acquisition manager) needs for the company's professional reputation.

My experience in the use of COTS has resulted in mixed emotions to its use. No doubt, the use of COTS provides the ability to leverage off of the commercial market's quantities and, thus, lower unit costs. However, the ruggedization of some COTS components for environmental reasons must occur. There is a fine line to the struggle between using COTS and the impact to potential reliability problems that must be prudently managed. Too much ruggedization makes COTS unaffordable. Not enough ruggedization makes COTS unreliable for the aircraft environment.

Also, the issue about the quantity of units and the period of time of the government procurement compared to the potential impacts to the basic design when the commercial supplier changes or closes its COTS production lines is an ongoing 'battle' with the use of COTS. The program manager will face the dilemma of a 'life-time' buy or change the system design – both requiring funds. In some cases the changes are anticipated, but in most cases not. Constant dialogue between the prime contractor (or systems integrator) and supplier is needed to limit the schedule and technical impacts to a program. However, the fiscal arena of U.S. government procurements does not necessarily support the ongoing and rapidly changes in technology. This conflict will continue until acquisition reform has a corresponding "fiscal reform". The best a program manager can do is to plan ahead for technological changes, make that a part of the contract with the prime or somehow otherwise protect those dollars in the budget.

For BMUP, use of COTS and NDI hardware was a primary decision for the acquisition strategy and plan. Systems engineering, consideration of the functional requirements, working with our industry partners up front in the IPT, and determining what the commercial market provides were the key to our success. The result of cost avoidances allowed the U.S. Navy to take advantage of many devices and newer technological capabilities that provided enhancements not available within the old obsolete subsystems. As well, the cost of these devices and the diminished requirement for extensive testing by using off-the-shelf components that had undergone prior testing drove the overall system cost down dramatically, allowing the available funding to be focused in other key areas.

4.2 Software Development

Software development has been an evolutionary process since the advent of computers. There is no need to discuss this history as it has become engraved into our society and acquisition world. The result of many acquisitions has been disastrous as learned during this evolving technological process.

For BMUP and many other systems I have been involved with, minimal software changes to the system provides a low technical risk. Key factors in the IPT's decision process were to minimize the software life cycle costs as well as operator-machine-interface presentations, thus capitalizing on existing training programs within the P-3C Fleet. Some programs' approaches to software reuse have been successfully using software cross compilers vice recoding into another Higher Order Language. BMUP made a conscious decision to force the use of the existing application software. However, the processor used by Update III could no longer be purchased due to obsolescence. Consequently, the IPT had to select a new COTS processor to use. Since the operating system software and software compiler are tied to the processor being used, modifications to the application program instructions (API) software were necessary to interface the operating system to the application program. As well, more efficient compilers are available and one was selected that is compatible with minimal impacts. BMUP will require some testing to ensure that the API logic works properly and efficiently. However, if rewriting code to a 'newer' higher order language is avoided, that can and WILL induce software errors. Again, technology trade-offs with affordability need to be the IPT's approach to risk mitigation.

4.3 Open Systems Architecture

The use of open systems architecture allows the use of commercial interface standards for basic computer interactions. No longer do we need to be tied to a specific militarized standard. This applies to tying multiple sensors, recorders, and the mission computer together for a viable systems product. Not all architectures are open systems, as claimed by some. A prudent review by the systems engineer will determine if a true open systems architecture exists, and testing will ultimately prove it.

Integrating a weapon system into an existing aircraft may or may not be able to take advantage of an open system architecture, depending on the level of the weapon system modification. If the program is planning to modify the entire avionics and weapon systems within the airframe, then proper funding can provide the ability to address open systems. Otherwise, if a program is integrating a new missile into the existing aircraft weapon system, then that effort is dependent on the existing system and its protocols. Factors that are impacted are what the interfaces are within the existing architecture: e.g. analog interfaces or digital interfaces. New weapons being developed today require digital interfaces for the most part. If a digital interface does not exist in the existing aircraft, then one needs to be developed (or provided as COTS/NDI) to allow the functional requirements to be satisfied. Or, a mechanism by which the analog data is converted to digital or vice versa must be utilized. These approaches are normally addressed in the systems engineering process by the IPT. The problem with conversion is the standard potential for inaccuracies and timeliness of the data. The software protocol of the information to allow interfacing from one device to another is extremely important. For legacy systems, attempting to ensure backward compatibility with older protocols can be a major detriment. This is not a military issue alone. Apple computer, with its introduction of the IMac in August 1998, has been hampered with the protocols used in its 56k baud modem and the advent of the Universal Serial Bus (USB). Since Apple used state of the art protocol with its 56k baud modem, and some of the smaller internet service companies have not upgraded to the newer protocol, many IMac users can't connect on the internet, thus upsetting the customer. Also, the USB in IMac is not interoperable with older printers, ZIP drives, etc. unless the customer has an interface adapter which other device manufacturers are now providing, or purchases a new peripheral device with USB. Apple made a conscious decision, knowing that the remainder of the market would adjust. Why didn't they make the IMAC backward compatible? I believe that cost is a main driver. In fact, I often use the mathematical term: 'Flexibility is directly proportional to cost. The more flexibility you want, the more it will cost you.' Apple wanted to produce a computer that would be affordable by the average household, competitive with the IBM PC and clones. If the requirements are to be backward compatible with legacy systems, then a cost trade-off analysis must occur to determine if it is better to replace the legacy systems than to try to keep interoperability with them. This philosophy is faced with military systems as well, especially in the C4I area

(Command, Control, Communications, Computers and Intelligence).

For BMUP, the IPT faced this same issue multiple times. A simple cost analysis very quickly determined that available funding would not allow the replacement of the entire system architecture. Besides, in order to lower life cycle costs for computer resources (software), the IPT wanted to use the application software with little modification, as mentioned earlier. We wrestled with the interoperability among the mission computer, recorders, printers, displays, acoustic processor, etc. We finally decided to maintain the interfaces backward compatible as a requirement, with options from the suppliers to allow alternative interfaces. The requirement for the backward compatibility provided two major provisions:

a. logistics commonality with the legacy systems.

b. potential logistics purchases for individual subcomponents for the legacy aircraft.

To date, this approach has been continuing. As the subsystems become available, the testers will validate that backward compatibility is met by testing the component first in the existing Update III Systems Integration Laboratory, then followed by testing in the aircraft.

4.4 Information Management

Technology advances through the use of computer automation and information management systems also allow the potential for elimination of paper (paperless acquisition) and real-time transfer of data. These systems are continually being developed and updated to meet the growing need for widespread use by the acquisition community and the warfighter.

For BMUP, the IPT established use of Video Teleconferencing, electronic mail and the use of a web site to transfer information. This allowed the members real-time transfer of documents vice normal postal carrier and has been quite successful. The contract specifically was written to provide this level of handling of unclassified data. Classified data was handled separately.

4.5 Configuration Management

Managing multiple series of the P-3C can be a challenge. Overwhelming Fleet needs and limited budgets have forced one-of-a-kind aircraft with specific sensors or capabilities. The impact to the maintenance personnel, logistics pipeline, training, and contractor has been enormous. The desire for a common configuration is budget-driven. The program manager must control the situation. A new weapon system integrated into the aircraft poses procurement problems. These are related to the expectations of the installers (contractor or government depot) with respect to establishing their work processes. Minimizing perturbations to a work process line maximizes efficiency of the work performed.

For any P-3C program, this problem has been addressed by ensuring that the drawings associated with the engineering change proposal are current and complete. Not being in a perfect world has forced the IPT to establish processes by which the Fleet and the installer work very closely when preparing and inserting an aircraft into a modification line. In some cases this is done by conducting a survey ahead of time at the Fleet location. This approach prepares the installer for the configuration that is about to be inducted into his line. As well, installations on existing older aircraft can be sometimes "unique". Holes never seem to line up just right, no matter how well the drawings depict them. Techniques that installers have recommended are: to not drill the holes for the equipment racks until the technician lines up the holes first with the airframe/existing rack; for pre-built electrical cables, ensure you have enough length for those cable bends, leave enough length for the unknowns, and put one end's connector on the cable after you've installed it to verify the actual length needed. This may sound unnecessary, and some may argue that the cable should be prebuilt and tested in the manufacturer before hand. There are many more techniques, but these few are ones that have impacted my programs more than once. The best of all worlds would be to have the proper funding to ensure all series of P-3C's were consistent. I doubt that will occur in my naval career.

5. TESTING

Before I venture too far, let me explain that I am a tester by trade and have had lots of experience testing. Through that experience, I have wrestled with the old question, "How much testing is too much?"

As a Deputy Program Manager, I continued to wrestle with my testers asking the same question. Each integration effort is different. Each one requires a logical thought process of reviewing the requirements that need to be verified, determining the best progression of how, when, and where to test it using the 'build-up' process, and finalizing the cost of testing. From that point begins review of the level of quality of the tests to be performed to allow the testers the confidence that the installed weapon system is acceptable for Fleet use. The struggle that occurs is that testers are like engineers – they would test forever and give themselves a 100% confidence that they have 100% quality. Unfortunately, there is not enough funding or time to achieve that level of confidence. Thus, the Program Manager will debate with the testers that old question.

5.1 Testing Process

Overall, testers need to be involved in the process from the start of any integration effort. They must understand the system to be tested, and can point out early on to the other IPT members the impacts of decisions during basic requirements definition through design reviews and buildup of engineering models. Program Managers need the testers to be involved so that they can plan the necessary funding to conduct the test later on. Early on, testers may find it difficult to visualize the final product that they will be testing. Experience and preliminary analysis and trade-offs are made to develop a preliminary project objectives and milestones, and test budget. These are then put into the Test and Evaluation Master Plan (TEMP). Throughout the program, the TEMP is revised and updated as the program progresses and more details of the design are made known. For integration of a weapon system into an existing program, the infusion of a new system into an existing one requires a level of testing different than a new-start program.

5.2 Regression Testing

Regression testing is the process whereby tests will be performed on a modified existing system to see if the new product being infused has any negative impact on the performance of the existing system. Regression testing is used throughout the entire system test process, including software code testing, subsystem level testing, and system level testing. The extent of regression testing to provide the tester the level of confidence is always debatable, as described earlier. Specific papers concerning regression testing have been written and are best to be referenced, especially in the area of software regression testing. For the Program Manager, it is best to work closely within the IPT to ensure that same level of confidence is experienced by all team members.

5.3 Simulation Use In Testing

The use of M&S has been stated earlier in Section 3.2, Simulation Based Acquisition. SBA would include the use of M&S in testing as one subset of the whole acquisition effort. As

stated earlier, the integration of weapon systems in existing aircraft may not find the use of M&S in requirements definition as fiscally prudent. However, M&S is extremely useful in the process of testing. The buildup process of testing has been well documented. (6) To lower test costs and increase confidence levels through the use of M&S are goals. The use of M&S is a effective tool during software testing, integration of the software into the target hardware, the target subsystem integration into the overall weapon system, the overall weapon system into the airframe, and finally the airframe ground testing, in order to provide a quality flight test. Validated simulation use is a norm for integrating software and hardware together in the laboratory. However, the use of simulation and stimulation is not always recognized for system ground testing in the installed aircraft. But it should. I have often said that it is very difficult for a software engineer who is attempting to diagnose a software discrepancy by observing the pilot's actions and corresponding weapon system responses in the cockpit while the aircraft is flying 300 knots. The use of the Air Combat Environment Test and Evaluation Facility (ACETEF) located at the Naval Air Warfare Center Aircraft Division is paramount to any integration effort. ACETEF provides modeling and simulation or stimulation to test all facets of any weapon system integration effort either at the isolated box level or installed in the aircraft. Systems associated with Electronic Support Measure systems, Electronic Countermeasure systems, Communications, Navigation, Radar, Electro-optics, Flight Controls and Displays, Electromagnetic Compatibility, Electromagnetic Interference, High Explosive Radiation Ordnance, Lightning and TEMPEST, can all be exposed to the environment before expensive flight testing occurs. ACETEF can really improve the quality of testing, the isolation and correction of deficiencies, and the confidence in the system performance as installed in the aircraft. This will improve the quality of flight testing to allow the testers to focus their attention on areas that have shown problems during simulation, and validate those areas in the flight regime. The use of ACETEF does not replace flight testing. However, ACETEF can and will lower costs compared to the 'fly-fix-fly' mentality of old.

Some other forms of simulation and stimulation have been used in P-3 testing. In the arena of acoustic processor testing, the Naval Air Warfare Center Aircraft Division has a Mobile Acoustic Test (MAT) van. This mobile van has tape recorders that replay existing acoustic signatures and send the signals via transmitters to stimulate the acoustic subsystem under test, or connected directly behind the antenna preamps. This van can be used during laboratory testing, ground testing, or flight testing. The MAT has been a very powerful tool used by P-3C acoustic testing community.

There are many more M&S "tools" available in the Department of Defense inventory. These were only a couple examples of those I have used with my programs.

5.4 BMUP Testing

BMUP has had test community participation from the start. Beginning with the generation of functional requirements, the tester has been an integral part of the IPT. As BMUP continues, the process of testing the modifications to the P-3C with BMUP installed will be refined. I suspect that continued discussions will take place between the testers, especially on what level of regression testing must take place with the non-developmental items and COTS products being used. The use of ACETEF will be necessary for a successful accomplishment, in my opinion.

6. RISK MANAGEMENT

All facets of procurement cannot be conducted without some level of risk. Risk management continues to be the key in effective weapons systems procurement and integration, thereby making the procurer the "smartest, most responsive buyer." The approach is for the IPT to identify what those risk areas are and develop a plan to mitigate those risks. In addition, the IPT should develop key performance parameters, their thresholds, and associated metrics by which to measure the progress towards thwarting those risks. In doing so, the IPT can best evaluate their performance in preventing these risk areas from becoming real problems. Risk management is not limited to technical areas, but involves all facets of cost, performance, schedule, and politics.

7. CONCLUSION

For the BMUP, the 'battle' has begun and the fronts are being formed. The Wingman and supporting divisions (i.e. the contractor and the subcontractors) have been chosen. V-Day won't occur until the first installation is complete and the Fleet goes on a mission. Until that day of complete success, many adjustments will have to be made to address the old acquisition phrase of "cost-schedule-performance" balancing. However, the approaches that the BMUP Team has undertaken make this balancing act manageable, with the strong desire to provide the true customer, the Warfighter, with a product that will serve him/her well.

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ROTARY WING STORES INTEGRATION (RWSI) PROCESS

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1. SUMMARY
This paper gives an overview of the Rotary Wing Stores Integration (RWSI) process which has been developed to improve the current process of weapons integration with helicopters in the area of separation analysis. Several tools have been developed to implement this process. Their function and position within the process will be covered.

Some background into the current process is provided. The current process is used to define the goals and requirements of the improved process. These requirements suggest the tools which are developed to implement the new process.

The resultant tools are explained, along with their position and function within the new process. The verification and validation process of the tools is shown. The results and improvements which result from the new process are explained. Finally, the resultant process is analyzed to suggest improvements and tools for the future process.

2. INTRODUCTION
During the helicopter/weapon integration process, one safety requirement is to assure that the weapon will separate cleanly from the helicopter during a weapon firing or jettison. Failure to accurately analyze or predict the separation characteristics of the weapon can have catastrophic effects. This danger is particularly acute during wartime, when time constraints are at a maximum.

The current process for clearing a firing or jettison envelope for a new helicopter/weapon combination is both slow and expensive. It starts with a low-fidelity (usually 2D) analysis of the jettison or firing at a few typical flight conditions. Once the basic separation characteristics of the weapon are determined, then a short flight test, or demonstration is conducted. The test matrix is determined by the number of assets available and the extent of the analysis. In order to maximize the firing/jettison envelope, tests are conducted at the questionable areas found in the analysis; the "edges" of the envelope. Due to budget constraints, the number of assets is usually small. This means that only a few flight conditions can be tested. Therefore, the amount of analysis, the accuracy of the analysis, and the confidence which the engineers have in their analysis is critical to clearing a large firing/jettison envelope.

During Desert Storm, army weapon integration engineers were operating under severe time constraints. The usual process was simply not an option. Little or no analysis was followed by an even more truncated test. The weapon integration engineers could not give the aviators a very large envelope and the decisions to do so were made with uncomfortably small amounts of data in hand.

A new process would be very helpful. The usual weapon integration process is far from ideal in all of the areas which are important: 1) Technical accuracy, 2) Speed, 3) Flexibility, and 4) Cost. A process which maximizes the jettison/firing envelope for a weapon, with a minimum number of required live firings would be ideal. The RWSI process and the tools developed to implement that process are an attempt to optimize the current helicopter/weapons integration process.

3. PROCESS NEEDS
The usual process is shown in Figure 1. Several tools or processes have the potential to improve this method.

3.1 Improved Analysis
A fast, accurate, and flexible analysis tool would improve the speed and technical accuracy of this process. A computer simulation model of the separation event could meet all of these needs. The usual process did and still does use computer simulations to analyze the expected separation characteristics, but with several shortfalls.

Currently, analyzing jettison/firing clearance characteristics are not a high priority and analyses are usually developed "on demand". This usually means that a completely new jettison/firing clearance analysis is developed for each new weapon/helicopter combination. This is both costly and time consuming; or in some cases it is quick, but inaccurate or less thorough than desired.

A flexible, accurate computer simulation tool in the hands of the weapon integration engineer would improve this process in several ways: 1) Improved flexibility, 2) Increased Control of the Analysis, 3) Speed, and 4) Control costs.

3.2 Improved Data Reduction & Analysis
A fast, accurate data reduction tool is mandatory to improve this process. The usual process uses high speed film in conjunction with the human eyeball to answer the question "did it hit the helicopter"? This methodology works for qualitative analysis (i.e. "yes" or "no") but gives limited (slow) quantitative results. Quantitative results are needed to validate the original analysis and to analyze trends in the separation

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

characteristics. This would give us the ability to check our work and improve the next analysis with lessons learned.

The usual data reduction process gives us the trajectory of the separation event, but that doesn't tell us what we really want to know: How close is the weapon to the helicopter? An accurate measure of this distance would give us a greater range of flight conditions to analyze for safety, which in turn results in a larger envelope for the aviator. An improved data reduction tool would improve this process in several ways: 1) Quantitative "feedback", 2) Increased Accuracy, and 3) Some speed increase. The theoretical improved process model is shown in Figure 2. This is the RWSI process in it's most basic form.

4. REQUIREMENTS

For the improved process model, requirements development is fairly straightforward because the goal remains the same. For the RWSI process, a group of potential users was convened to develop requirements. Technical obstacles and financial constraints were taken into consideration.

4.1 Accuracy

For a helicopter/separation simulation tool, accuracy is key. A full top to bottom verification of the computer code is required to eliminate errors. Also, all efforts must be made to ensure that the input data is accurate. These requirements are standard for any computational effort. Accuracy in the simulation/analysis directly translates to time and cost savings during flight testing.

Requirements development for the data reduction and analysis is key because the results will necessarily be used to validate the simulation. If the uncertainty in your data reduction is 1/3 meter, then for safety the separation envelope is defined by the flight conditions where the separation distance becomes 1/3 meter. The smaller the uncertainty, the more you can "push the envelope". The question becomes "how close is close enough"? Technical obstacles and financial constraints are also major considerations. For the RWSI project, it was decided that 6 inches (about 0.15 meters) would be a major improvement over the current process.

4.2 Flexibility

The flexibility to model several helicopter/weapon combinations would be a major improvement. However, flexibility is not enough if it costs in either speed or accuracy. The idea would be to develop new models with minimum data requirements without having to rewrite the simulation code each time, and *without losing accuracy.*

For a new data reduction/analysis system, flexibility means having a system which requires minimal changes in the way the test community conducts the testing or collects the data. This flexibility translates into time and cost savings during the test.

4.3 Speed

A hyper-accurate simulation or data reduction system is no improvement if it takes months to get an answer. Increases in speed in both the simulation/analysis and the data reduction/analysis steps of the process translate directly to cost savings. The key is to require minimal inputs and modifications to the simulation or data reduction/analysis system for any given separation analysis.

5. TOOLS

The tools developed during the RWSI project specifically target the areas of separation simulation and data reduction/analysis in an attempt to improve the current process. Several new tools were developed and fit together into a system which improves both "ends" of the current process and effectively creates a new process, the RWSI process. The RWSI process is shown in Figure 3. A short description of some of the new tools are in the following paragraphs.

Helicopter Armament Stores Separation (HASS) Trajectory Generation Program (TGP) calculates the trajectory of the separating weapon/equipment based upon initial conditions, an aerodynamic math model, and the rotor wake flow field model.

Graphical Helicopter Configuration Builder (GhConf) combines geometry and simulation models of the particular aircraft, weapon, and ejector rack for the configuration to be simulated. This tool is the first key to the flexibility of the system.

Helicopter Maneuver Program (HMP) is a modified version of the *Evasive Maneuver Criteria Evaluation Program (EVMCEP).* This program models the helicopters and is the second key to the flexibility of the system.

Computer Aided Store Separation Analysis System (CASSAS) is used to visualize trajectory simulations, to reduce test data, and to visualize the data reduction results. CASSAS extracts six degree-of-freedom (6-DOF) data from two-dimensional (2D) digitized images.

Clearance and Collision Detection Code (CLRANC) calculates the minimum miss distance between the separating weapon and the helicopter using the trajectory, the helicopter's maneuver characteristics, and the geometry models of the helicopter and store.

Graphing tools, image processing tools, and some format conversion utilities are also included in the RWSI system. These tools allow the outputs to be used in reports and shared with others.

6. VALIDATION

Validation of the RWSI software tools was a two-step process: 1) Validate the CASSAS data reduction tool, 2) Use CASSAS to validate the simulation tools. Validation of the CASSAS software had 3 steps:

1) Laboratory Testing - Extracting 6-DOF data of standard geometric shapes using computer-generated

objects within simulated scenery. The objective was to measure intrinsic system errors under ideal conditions.

2) Ground Testing - Extracting 6-DOF data of objects in still 2D video images and recordings of graphical computer simulations. In both cases the correct answers are known either from direct physical measurement or advance knowledge of the simulation data.

3) Flight Testing - Extracting 6-DOF data of real weapons from digital images of real flight tests.

This effort showed that the accuracy of the CASSAS system is dependent upon the image-to-object size ratio, or how large the objects appear in the image, and also whether the movement of the objects within the image is perpendicular or parallel to the camera line of sight. This result is not unexpected, since this is also how the human eye works.

A flight test was conducted to collect film images of several combinations of weapons and stores separating from helicopters. The CASSAS software was used to obtain the actual trajectory of these separation events. The results were compared to the trajectory calculated by the simulation code.

6.1 Additional Validation

Additional validation data was provided by the U.S. Navy, during a helicopter/weapon integration effort which was being conducted at the same time. RWSI trajectory predictions were compared to these test results. The comparison uncovered major errors in the simulation code. These errors were: 1) A previously undetected sign error in a coordinate-transformation calculation, 2) The store mass properties data used in the prediction was outdated and incorrect, and 3) RWSI simulation does not take into account helicopter body effects on the airflow. The first two problems were corrected, but the third problem requires additional research and data to quantify. These errors reinforced the importance of the verification process and the importance of the *feedback* capability of the RWSI process. By finding these errors and correcting them, the quality of subsequent predictions has been increased. Additionally, by finding a shortcoming in the RWSI code, the analyst can now make more informed decisions when simulating trajectories and developing test matrices in areas where the airflow around the helicopter body will affect the separation event.

6.2 Validation Results

Both the test results and the simulation were used as inputs to the CLRANC code to determine how close the simulation results can predict the miss distance of the separation event. Typical results are shown in Figure 4. The dip in the middle of the chart is the point where the store falls past the helicopter skid. This is the miss distance of greatest interest.

7. RESULTS

The development of a new process and the appropriate tools to implement that process has provided many improvements in the separation analysis portion of the helicopter/weapons integration process. The major areas of technical accuracy, speed, cost, and flexibility have all been improved.

7.1 Technical Accuracy

A simulation tool has been developed and verified for analysis of store separation events. Several aircraft and store combinations have been validated. A data reduction tool has been developed and validated to obtain the actual 6-DOF trajectory from 2D digital images.

7.2 Flexibility

The helicopter simulation program offers unprecedented flexibility with the ability to model multiple helicopters. The Ghconf (configuration builder) software increases this flexibility by allowing combinations of ejectors, launchers, and stores in various combinations. Currently, 6 helicopters, 6 ejector racks, 7 launchers, and 4 weapons have been modeled. The data reduction tool (CASSAS) offers flexibility because the camera position relative to the separating store is not required to be known in advance. Also, the separating store does not need to be marked or prepared in any special way before the test. Finally, by controlling the simulation process, the weapons integration engineer has the flexibility to investigate the maneuvers and configurations he/she chooses. Parametric studies can also be conducted in a reasonable amount of time.

7.3 Speed

The RWSI tools offer good accuracy within a very reasonable time. A completely new helicopter aerodynamic/performance model is obviously the most difficult to accomplish, and can take several weeks to input data and verify accuracy. Creating a new geometry model for an entire helicopter can also take several weeks.

More often, only a new store needs to be modeled. Given appropriate mass properties and aerodynamic data, a new store can be modeled in a couple of hours. The corresponding geometry model can be constructed in a couple of hours, possibly up to a couple of days, depending on the complexity.

Once the models are in place, using them to calculate trajectories takes little time. A new maneuver for a helicopter can be calculated in under 5 minutes. A trajectory can be calculated with the new store and new maneuver in under 5 minutes. The CLRANC code is the most computationally intense, and can take 15-20 minutes to obtain the miss distance at each time step of the calculated trajectory. A very detailed test matrix can be developed in less than a day.

After the test, the CASSAS software can reduce the flight test data quickly, typically less than one hour per event. Developing and digitizing the film determines the speed of the data reduction. This means that the data can be completely reduced before the next flight. Dangerous trends can be identified or unnecessary flights can be skipped.

7.4 Cost

A fast and accurate simulation, analysis, and data reduction tool cuts costs in many ways. Simulating separation events shows which conditions are almost certainly safe and shows which conditions may be less safe. This allows the test planners to concentrate the testing in areas of concern. The result is a larger separation envelope for the aviators, with less testing. A flexible simulation code cuts costs by eliminating much redundant software development. Fewer data inputs decreases the data collection time and data entry time. Increasing efficiency in data reduction cuts costs by lowering labor and equipment costs.

7.5 The Future

The RWSI process is only an improvement over the previous process. Many improvements can still be made. Some areas to concentrate would be:

Digital Cameras - Replacing film with digital cameras is underway in many industries. In the flight testing arena, eliminating the film developing and digitizing process will save time and money.

Simulation Upgrades - The RWSI trajectory prediction code has several areas which could be improved to increase accuracy. Improved downwash modeling and helicopter body effects top the list. Additional research would be required and/or advances in computational fluid dynamics capabilities.

Computing Power - Continuous improvements in computing power will enable advancements in speed and portability of the current codes. Also, increasing computing power will enable capability upgrades to be added in the areas of visualization and modeling of complex airflows.

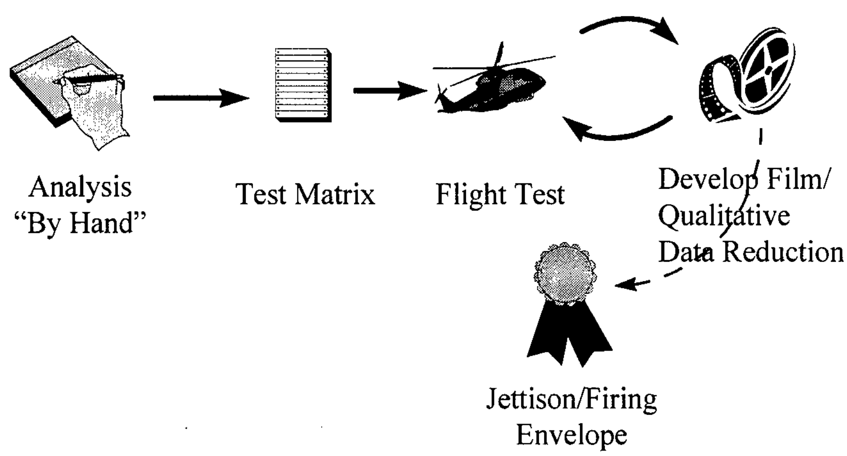

Figure 1 Typical Envelope Development Process

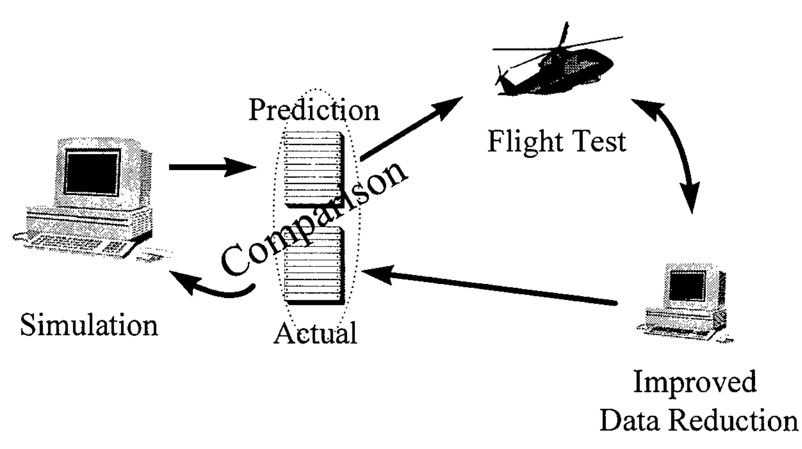

Figure 2 Theoretical Improved Process with Feedback

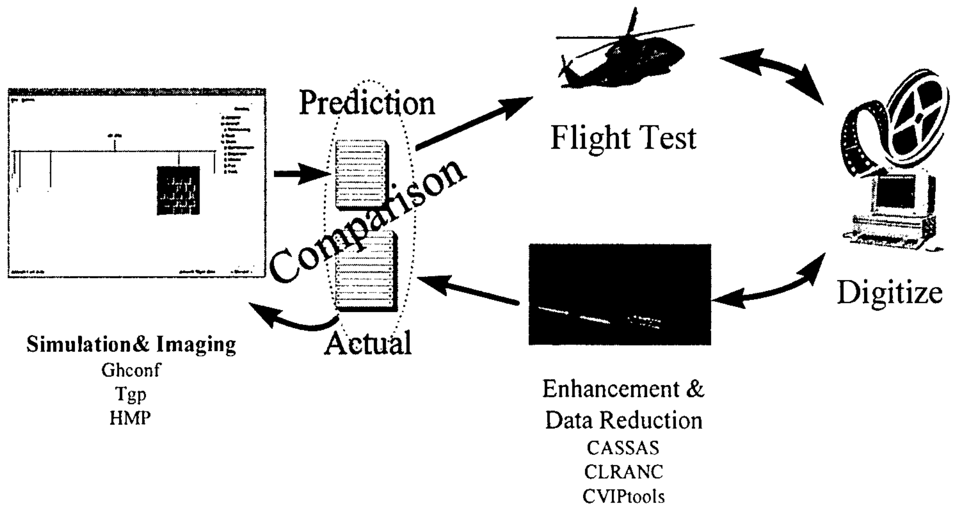

Figure 3 RWSI Process

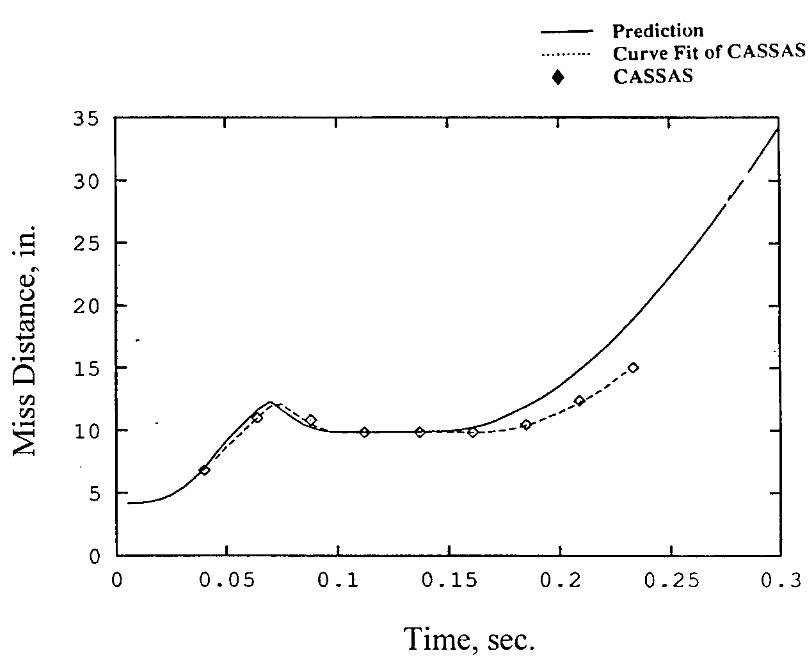

Figure 4. Typical Miss Distance Calculation

Helicopter / Weapon System Integration
- An Overview and Synopsis of AGARD LS 209 -

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SUMMARY

The helicopter is fast approaching a half century of service as a weapon system. From humble beginnings after World War II, largely in the roles of observation platforms and search and rescue vehicles, rotorcraft have evolved to a principal in the modern battle scenario. In the war at sea, the helicopter forms an integral part of a task force capable of launching devasting firepower at surface and subsurface targets. In the airland battle, technology has made the helicopter into a tank killer, troop transport and night observation platform. Finally, in the most unlikely arena, air-to-air combat, modern weaponry has shown the helicopter to be effective against even high performance tactical aircraft.

Under ideal circumstances a new helicopter design is being directed towards certain weapon capabilities, making the weapon integration discipline a mature part of the design process. However, the rapid pace of weapons development often leads to airframe modification programs and weapons kits make high-technology weapons subsystems a part of older aircraft. In such cases, the system integration efforts is sometimes reduced to "cut-and-try". At best, such an approach may be inefficient, at worst it may be unsafe.

The AGARD Flight Vehicle Integration Panel and the Consultant and Exchange Programme decided to set up in 1997 the Lecture Series 209 on Helicopter/Weapon System Integration. The Lecture Series considered the problems of integrating externally mounted weapons on helicopters with the focus on aeromechanical, structural and operational issues. New aspects in the field of helicopter / weapon system integration were addressed and strong emphasis was placed on the lessons learned from recent experiences in actual development programs. Case histories of weapons integration on the AH-64 Apache, the RAH-66 Comanche, the EH-101, and the Tiger were presented and discussed.

This paper is intended to give an overview of the material provided in the lectures and to draw some essential conclusions from the discussions.

1. BACKGROUND

In the modern battle scenario helicopters form an integral part of the military forces and are used in a broad variety of missions and tasks. In Figure 1 the main mission tasks of military helicopters are outlined, including the logistical or transport operations, like

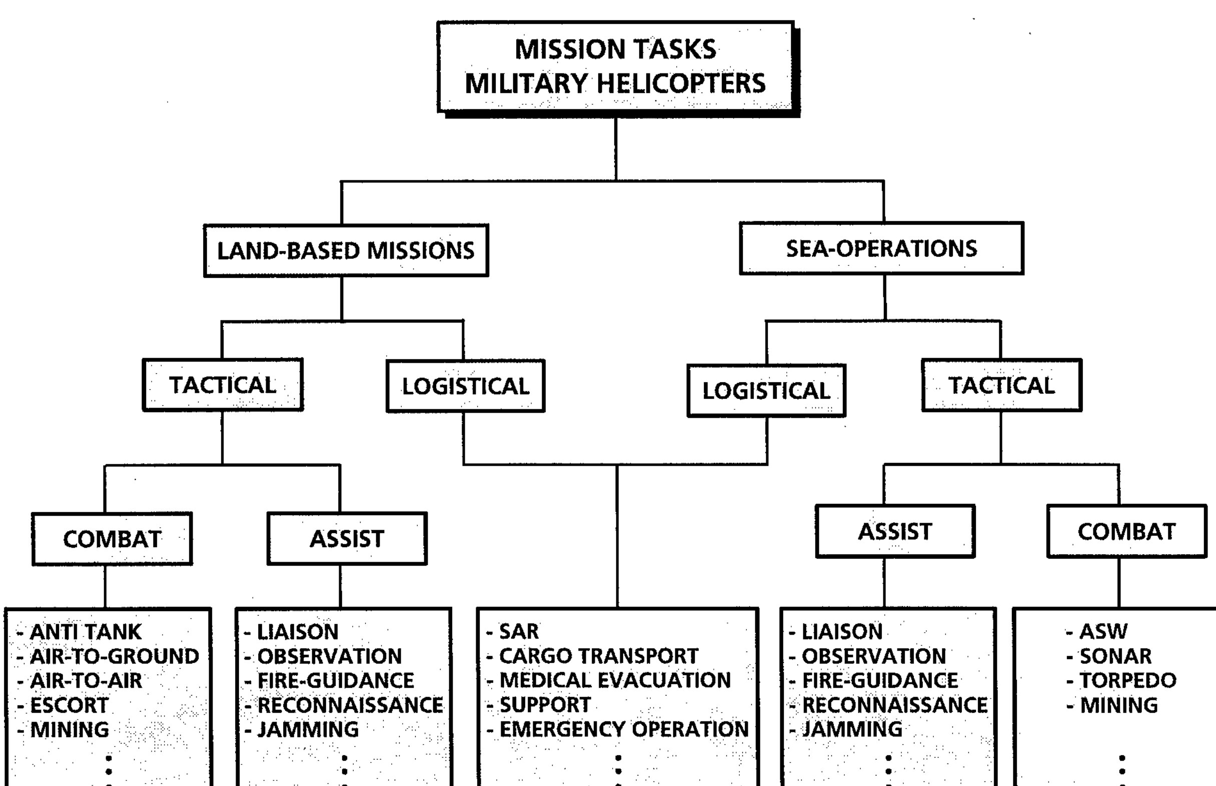


Figure 1: Military Helicopter Missions

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

- SAR,
- cargo transport (in board or underslung),
- medical evacuation,
- support,
- emergency operations,

and the tactical operations in the combat and assisting role
- antitank,
- air-to-ground,
- air-to-air,
- escort,
- mining,
- ASW,

as well as liaison and observation tasks, fire guidance, jamming etc.

It is obvious that the originally "clean" helicopter needs to be equipped with task oriented installations, in particular with weapon systems for the tactical operations, including guns, rockets and missiles. When arming helicopters with external weapons, it is general practise to equip the aircraft with weapon systems which are already in use on or are derived from land based vehicles, or from fixed-wing aircraft. Three different situations may be considered:

– The weapon system is installed on already flying helicopters in the same configuration as used on the land based vehicle or fixed-wing aircraft, simply by bolting - on the limited number of available hard points on the fuselage. This leads to complex weapon carrier structures, and the support structure and the weapon system itself substantially affect the helicopter's performance and handling qualities.
– The Weapon carrier for already existing helicopters is redesigned and/or the helicopter is partially modified in order to minimize the penalties of the weapon system integration as much as possible. This approach is often used, in particular for modern helicopters and modern weaponry requiring complicated interfacing between the helicopter and the weapon system.
– Already in the design stage of the helicopter, the configuration is established that minimizes the degradation of the characteristics of the integrated helicopter / weapon system. This may range from the relatively simple solution as the introduction of an aerodynamically effective wing as weapon carrier, to a weapon system aerodynamically integrated in the fuselage.

Depending on the specific solution, the installation of external weapons may cause substantial problems with respect to helicopter performance, handling qualities, structural mechanics, and vibrations and acoustics. In addition, the complicated problems produced by a weapon system inherent set of compatibility conflicts between the host helicopter and the weapon have to be quantified and solved during design, test and evaluation, and operational assessment. This includes solutions for store separation and for special effects caused by weaponization of the helicopter, like debris damage, exhaust plume erosion, temperature effects etc.

For a specific weapon system integration program the effects discussed above have to be considered in view of the user-defined operational requirements for the overall helicopter/weapon system (Fig. 2). This includes the requirements for the operational flight envelope (Figs. 3, 4), for agility (Fig. 5), safety / survivability (Figs. 6, 7), handling characteristics (Fig. 8), and efficiency of the system (Fig. 9). The integrated helicopter/weapon system has to demonstrate compliance to these requirements in order to enable the pilot to successfully fulfill the required military mission and to provide satisfactory mission performance.

OPERATIONAL FLIGHT ENVELOPE

TEMPERATURE/ALTITUDE RANGE
NIGHT/ADVERSE WEATHER CAPABILITY

AGILITY

PERFORMANCE
MANEUVERABILITY

SAFETY/ SURVIVABILITY

REDUNDANT/FAIL-SAFE DESIGN
DAMAGE TOLERANCE
PROTECTION

HANDLING CHARACTERISTICS

FLYING QUALITIES
GROUND HANDLING

EFFICIENCY

EQUIPMENT
PAYLOAD
ARMAMENT

Figure 2: Operational Requirements for Helicopter / Weapon System

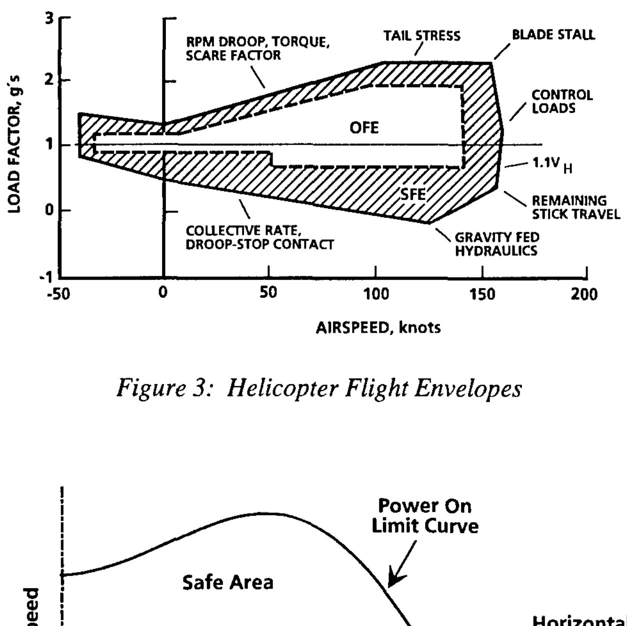


Figure 3: Helicopter Flight Envelopes

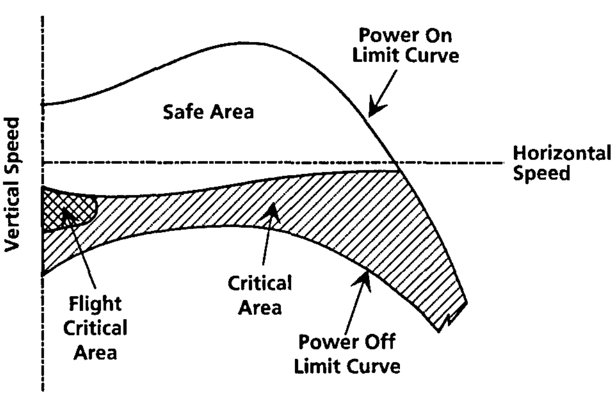


Figure 4: Typcial Helicopter Store Separation Flight Envelope

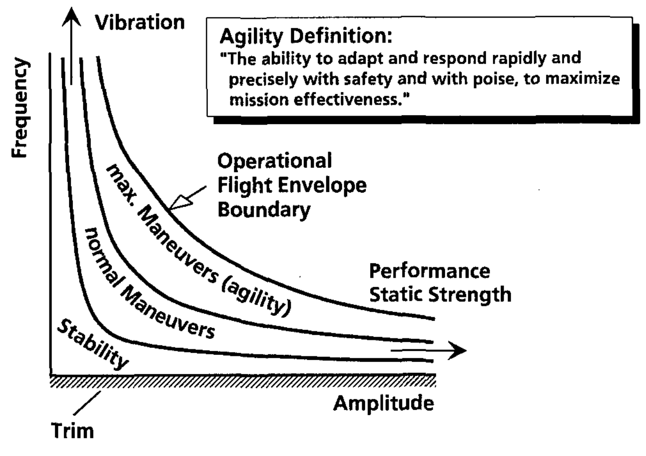


Figure 5: Helicopter Flight Dynamics

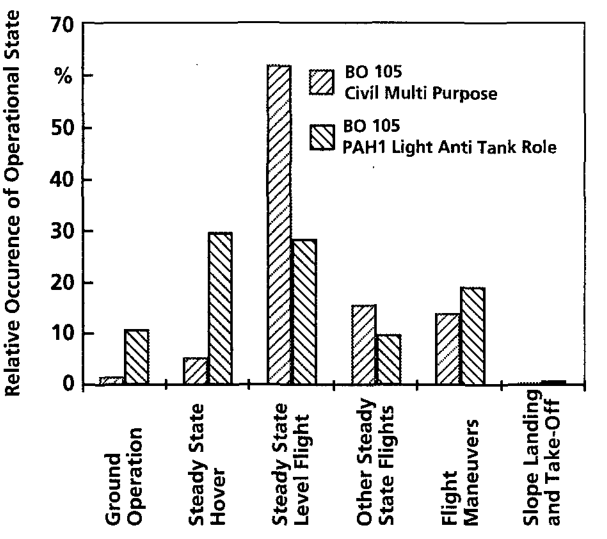


Figure 6: Civil vs. Military Mission Spectrum

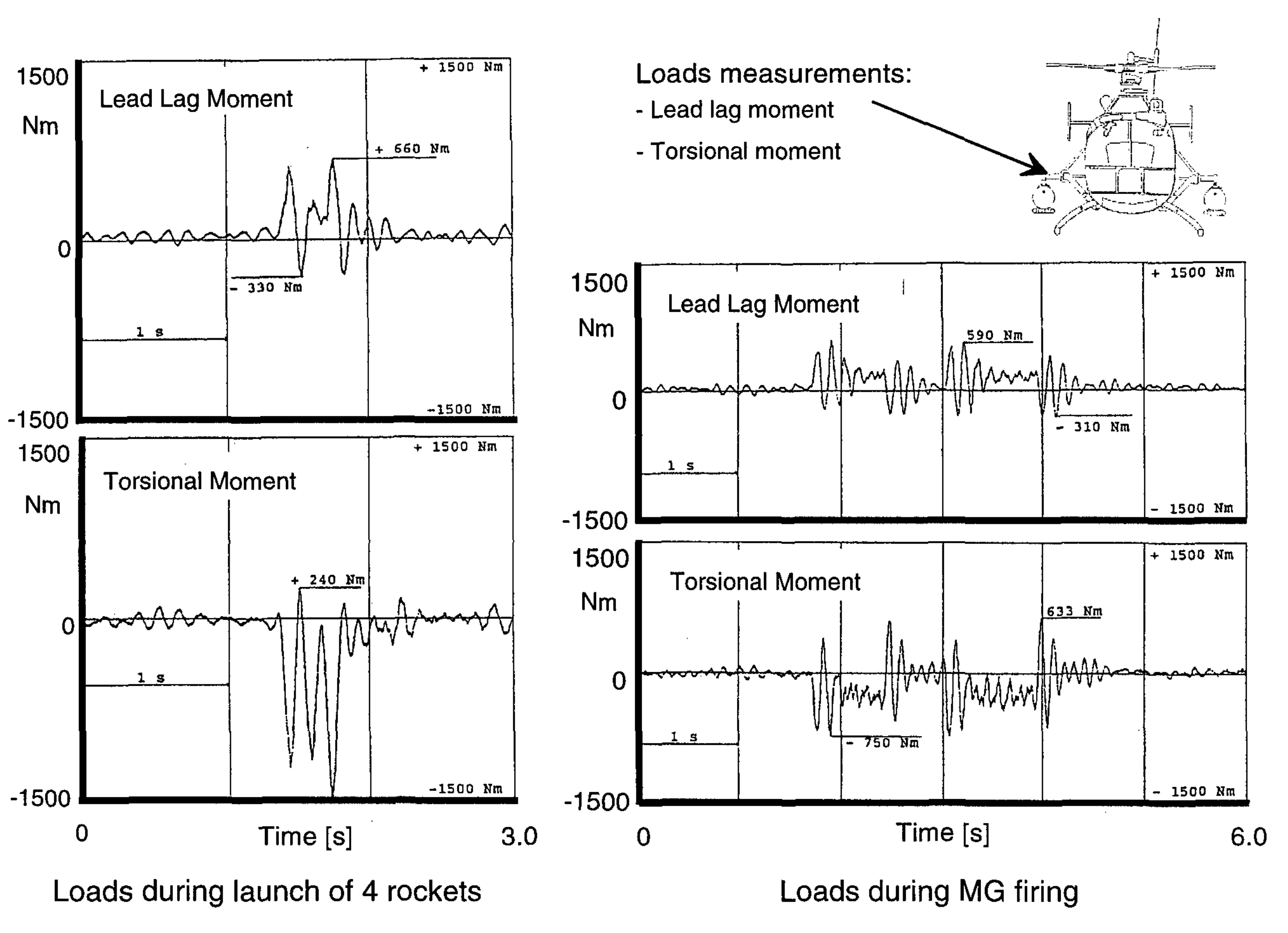


Figure 7: Loads on a BO 105 Weapon Suspension

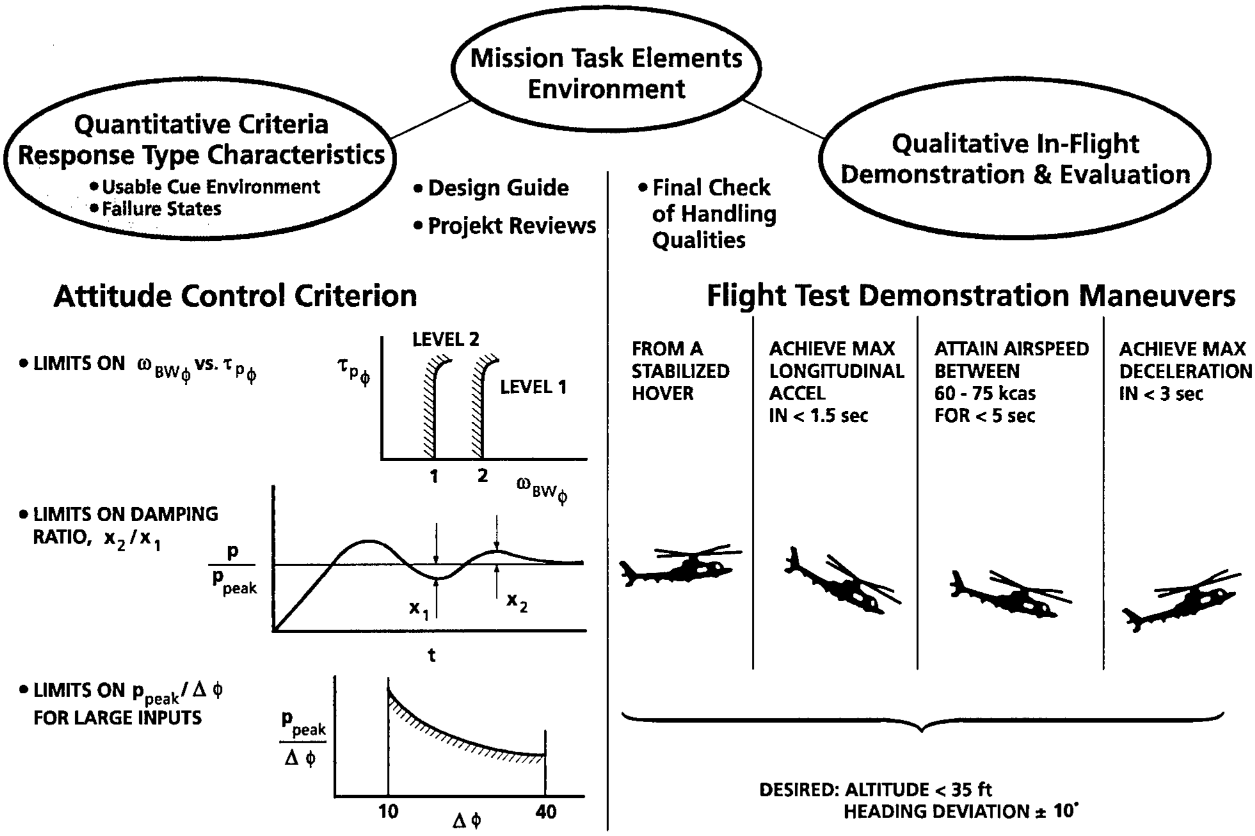
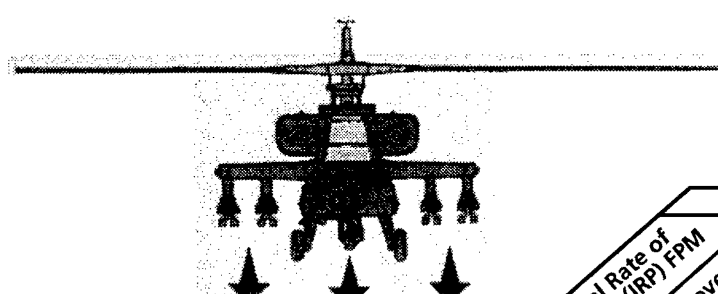


Figure 8: Quantitative and Qualitative Handling Qualities Evaluation



Missions	Wing	Gun	Wing	Performance*: Vertical Rate of Climb (IRP) FPM	Max Level FLT Speed (V_H) KTS	Mission Duration Hours
Anti-Armor (Defense) Mid-East Primary Mission 4000'/95°F	4 HF	320 RNDS	4 HF	1450	154	1.83
Anti-Armor (Defense) Mid-East 4000'/95°F	4 HF	1200 RNDS	4 HF	450	151	2.67
Anti-Armor (Defense) Mid-East 4000'/95°F	8 HF	320 RNDS	8 HF	450	147	1.9
Anti-Armor (Defense) Europa 2000'/70°F	8 HF	1200 RNDS	8 HF	990	148	2.5
Anti-Armor (AirCav) Mid-East 4000'/95°F	4 HF	1200 RNDS	4 HF	960	153	1.83
Covering Force (Air Cav) Mid-East 2000'/70°F	4 HF 19 RKTS	1200 RNDS	4 HF 19 RKTS	860	150	2.5
Covering Force (Air Cav) Europa 4000'/95°F	19 RKTS	1200 RNDS	19 RKTS	860	155	1.83
Airmobile Escort Mid-East 2000'/70°F	38 RKTS	1200 RNDS	38 RKTS	780	153	2.5

*Based on actual aircraft weight

Figure 9: Armament Options → Mission Flexibility

2. OBJECTIVE AND STRUCTURE OF THE LECTURE SERIES

Based on the excellent work of the AGARD Flight Mechanics Panel Working Group 15 and on the related report AGARD-AR-247 [Ref. 1], this Lecture Series on Helicopter/Weapon System Integration intended to address new aspects in this field, with a strong emphasis placed on the lessons learned from recent experiences in actual development programs (Fig. 10).

Session 1: Aerodynamics and Flight Mechanics
- Performance
- Handling Qualities
- Store Separation

Session 2: Structural Mechanics
- Loads, Dynamics/Vibrations, Acoustics

Session 3: Special Effects

Session 4: Case Histories
- AH-64 Apache (H. M. Dimmery, MDHS (Boeing))
- RAH-66 Comanche (W. Harper, Boeing-Sikorsky Comanche Program)
- EH 101 (R. McBeath, GKN Westland Helicopters)
- Tiger (R. Wennekers, Eurocopter Deutschland)

Figure 10: AGARD LS 209: Helicopter/Weapon System Integration

The lectures started with general presentations on aerodynamics and flight mechanics, structural mechanics, and special effects related to specific weapon categories like droppable stores, forward firing ordnance, articulated weapons, and dispensers. This information dealt with modern approaches and procedures in respect to the expected aeromechanical interface problems, and formed the basis for the discussions on the second part of the program, the case histories.

For modern military helicopter systems

- Boeing Helicopters (McDonnell Douglas Helicopter Systems): AH-64 Apache,
- Boeing Defense & Space Group, Helicopter Division/ Sikorsky Aircraft Division, UTC: RAH-66 Comanche,
- E.H. Industries, Inc.: EH 101, and
- Eurocopter: Tiger

the specific solutions for the helicopter weapon systems integration problems were presented. The lectures intended to explain more fully the physical phenomena, and to provide the actual experience base in this field.

The material presented during the Lecture Series is provided in Reference 2 and includes a detailed discussion of the subjects. In this paper selected aspects of the case histories will be presented with the objective to cover the broad spectrum of specific solutions for modern helicopter/ weapon systems, and to allow to draw some general conclusions.

3. AH-64D APACHE LONGBOW (HUGH M. DIMMERY)

The AH-64D Apache Longbow (Fig. 11) represents a significant enhancement in the evolution of attack helicopters. It is a fourth-generation precision weapon system that is totally integrated. The high level of integration provides an efficient and operationally effective system and gives commanders at all levels the ability to meet modern battlefield requirements ranging from peace-keeping to major regional conflict. Some of the AH-64D Apache Longbow capabilities and its inherent design features are described.

Figure 11

The Apache Longbow represents a significant improvement to the combat-proven AH-64A. The most distinguishing external characteristic of the Apache Longbow is the mast mounted assembly (MMA) which houses the fire control radar (FCR) and is mounted on top of the rotor system. Internally, the AH-64D is totally new. The FCR is coupled with the advanced crewstation, a significantly improved navigation and communication system and an integrated digital information system. Figure 12 illustrates the major system enhancements incorporated in the AH-64D.

The addition of the fire control radar and fire-and-forget missile was not a simple addition of another weapon on the Apache. The FCR and the missile were integrated into the total Apache weapons system. Simply put, the FCR and the radar frequency interferometer (RFI) added two additional sources of target information that were integrated with the existing sights and sensors. The target acquisition and designation system (TADS), the pilot night vision system (PNVS) and the integrated helmet and display sight system (IHADSS), for both the pilot and copilot-gunner, were accommodated in the integration activity. The objective was to maintain consistent crew selection logic regardless of sight and weapons system selection while reducing the workload through automation and cognitive aids. Similarly, the integration of the Hellfire missile was considered as an enhancement to the current capability and not merely a stand-alone capability. As a result, the totally integrated sight and weapon system currently supports the ability to engage multiple targets with any sight and weapon combination (Figure 13) except for the Hellfire II missile that requires the laser.

Additionally, the sights can be employed in a cooperative mode through the link mode or independently by either crew member. The integrated sight and weapon subsystems provide the crew with the capability to select the appropriate sight. Display and weapon for the tactical situation. Obviously, the crew can override either selection in real time or can tailor the system response based on their preferences.

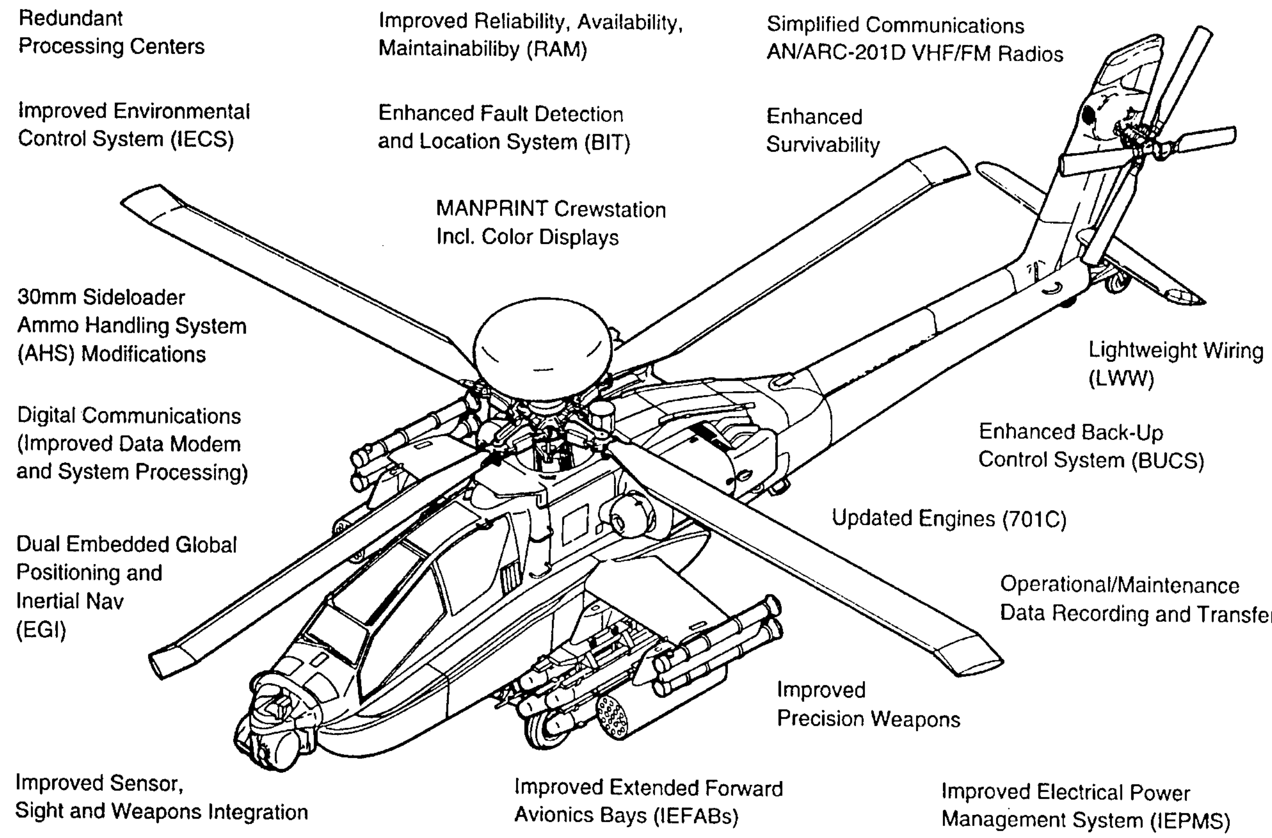


Figure 12: AH-64 D Apache: System Enhancement

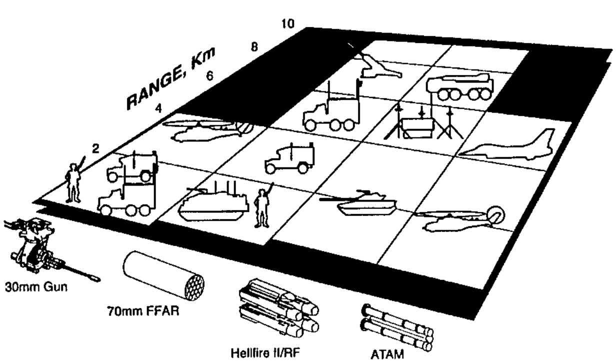


Figure 13: AH-64 D Apache: Integrated Sensors and Weapons

4. RAH-66 COMANCHE (WILLIAM H. HARPER)

The RAH-66 Comanche (Figure 14) is the US-Army's newest helicopter for the primary missions of armed reconnaissance and light attack, with embedded air combat capability.

Comanche will correct light fleet deficiencies such as marginal night and adverse weather capability; location / navigation inaccuracies; inability to self-deploy to over-seas theaters of operations; inadequate reliability, performance, and survivability; and high operating costs. System improvements include lightweight composite airframe structures; a protected antitorque system; low-vibration, high-reliability rotor system; second generation target acquisition and night vision sensors; and an advanced electronics architecture. Comanche has an integrated, automated cockpit, worldwide navigation capability, secure communications, and electromagnetic pulse and interference-hardened avionics. It incorporates crashworthy design features; wheeled, retractable landing gear; and will be self-deployable to Europe, the Middle East, and Latin America. Comanche will perform both reconnaissance and attack missions, utilizing aided multiple target acquisition, classification, prioritization, and handover capabilities. It will have a dash speed in excess of 170 kn and a vertical rate-of-climb in excess of 500 feet-per-minute at high-altitude/hot-day conditions (4,000 feet and 95°F). Armament features include fire and forget radio frequency (RF) and semi-active laser HELLFIRE missiles, air-to air (ATA) Stinger missiles, 2.75" rockets, and a 20 mm turreted gun. Comanche will be integrated within the Army Aviation force structure to compliment the AH-64 Apache helicopter in heavy divisions, and provide armed reconnaissance and attack capabilities in light divisions.

Figure 14

During the design process trades were conducted to compare attributes of internal versus external weapons configuration. Configurations used in the trades are shown in Figure 15. It was determined early that the selection of external or internal stores arrangements had a major influence on the basic airframe. The internal weapons installation lends itself to a primary structure backbone (or central boxbeam arrangement). This permits a modular type construction having vertical parting planes onto which equipment packages can be mounted. The boxbeam also provides crashworthiness capability preventing plowing during forward crash, and it offers torsional rigidity.

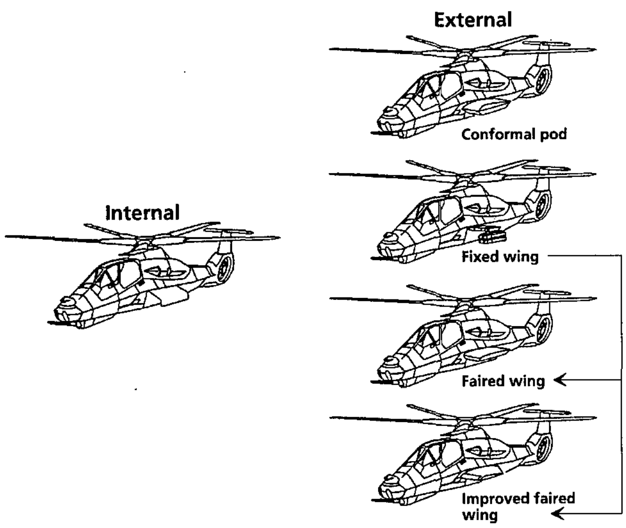


Figure 15: RAH-66 Comanche: Internal vs. External Weapons Configuration

The external weapons arrangement on the other hand, lends itself to a more conventional semimonocoque construction. The external stores support structure attaches to the fuselage via bulkhead or frame-mounted fittings.

It was also recognized early in the design process that an unfaired external stores arrangement would not meet the Comanche low-observable requirements. The drag of the unfaired external stores configuration also became an issue when the T800 engine power became fixed. The attributes of internal and faired external weapons configuration were thoroughly examined before the retractable internal configuration was selected for Comanche.

A 1/6th-scale airframe aerodynamic wind tunnel test was conducted having the following objectives:

- Define the total airframe lift, drag, and stability characteristics and the breakdown by component.
- Measure surface static pressures at various inlet and other critical locations.
- Define and correct any sources of aerodynamic deficiencies in the flow quality.
- Evaluate the drag and stability of external stores.

The model was also designed to simulate flight with the retractable weapons bay door opened both with, and without, missiles. The fuselage cavity was simulated for this test with the doors open. The EFAMS extended-range tanks and additional HELLFIRE loadouts were also fabricated and tested.

As shown in Figure 16, opening the weapons bay doors and installing external weapons increases the drag significantly. Opening the weapons bay doors, and installing a four HELLFIRE and two air-to-air Stinger (ATAS) load, increases the drag 8.17 ft2 of which 6.71 ft2 is due to the missiles. Adding the EFAMS pylons, and an addition four HELLFIREs per side results in a total drag penalty of 15.09 ft2. For self-deployment missions, the external fuel tanks combined with the EFAMS pylon increases drag by 5.2 ft2. Dropping the tanks reduces the drag 2.92 ft2.

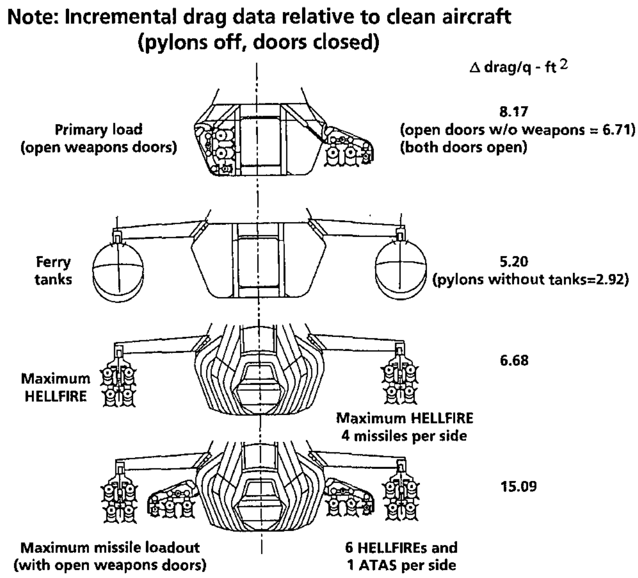


Figure 16: RAH-66 Comanche: External Stores Configurations

5. EH101 MERLIN (J. ROWLIE McBEATH)

The EH101 (Figure 17) is a family of naval, utility and civil helicopters whose design and development have benefitted from the different requirements of each of these operating regimes.

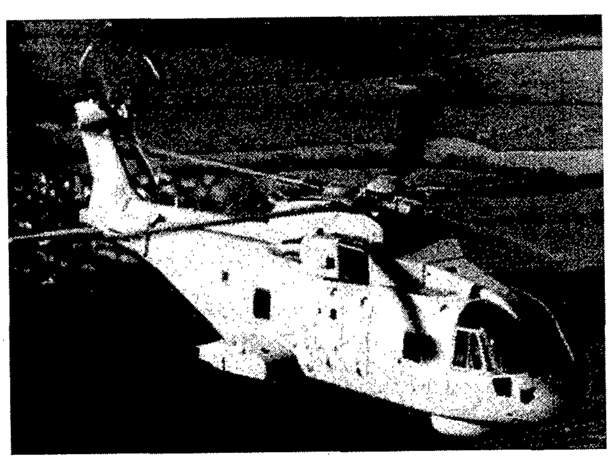


Figure 17

The British Royal Navy's Merlin Helicopter Maritime Mk.1 is the first EH101 variant to be delivered to its customers. In its requirements the Royal Navy specified some key aircraft performance markers for Merlin, as part

of the specified performance of the overall system. The first two are speed and endurance to allow operations at extended ranges to permit quick reaction to, and attack of, submarine targets. EH101 can carry up to four lightweight torpedoes or depth charges. Its typical speeds are: dash at up to 150 knots; economical cruise at up to 140 knots on three engines; or else loiter (for maximum endurance) at up to 120 knots on two engines, providing some three hours on station searching well ahead of the fleet.

The third feature is an integrated mission system which can process data from a comprehensive suite of sensors. This gives EH101 an independent capability to search for, locate and attack targets. Independent (or autonomous) operation means having no need to call on the support of another unit to detect, classify or prosecute an evading, fast, quiet submarine. Versatility was a fourth key requirement, to enable the helicopter to carry out a wide variety of roles and to respond quickly to emergency tasking flash points around the world.

The weapon system that comprises Merlin HM Mk.1 and the Type 23 frigates on which it will be based initially has been designed to provide maximum operational efficiency by the use of advanced technology to reduce crew workload while maintaining a very high state of readiness and aircraft availability (Figure 18).

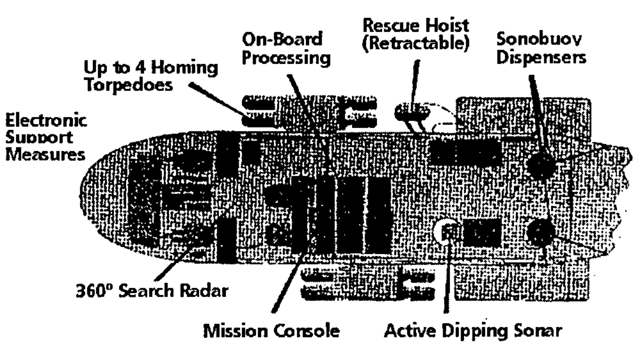


Figure 18: EH 101 Merlin: Cockpit and Cabin Layout

The Primary Missions of Merlin are active and passive Anti Submarine Warfare and Anti Surface Warfare. In the ASW role, Merlin will have a simultaneous active and passive sonar capability. The capability of EH101 to auto-time share sonobuoys will be double that of the Sea King, while the mission computer will process tactical data to achieve an attack solution.

Its autonomous capability is the feature that makes EH101 unique among ASW helicopters. Based on its own information, or on initial contact data passed on from another unit, EH101 will be able to locate, identify and attack without assistance.

The integration of Merlin's weapons with the remainder of the aircraft has had to take into account the double-headed nature of the EH101 programme: the EH101 aircraft with its core avionics and other existing basic and naval variant features, for which EHI is responsible; and the aspects of Merlin that are unique to this particular aircraft for which, as part of the whole Merlin programme, Lockheed Martin ASIC is the prime contractor.

So far as weapon integration is concerned, most of the systems involved already form part of the baseline EH101, although they need to be interfaced with UK-specific equipment such as the radar and sonics.

Figure 19 reveals a fairly conventional integration programme with the delivery of the first production aircraft achieved in 1996, and the first aircraft flying operationally at sea in 2000.

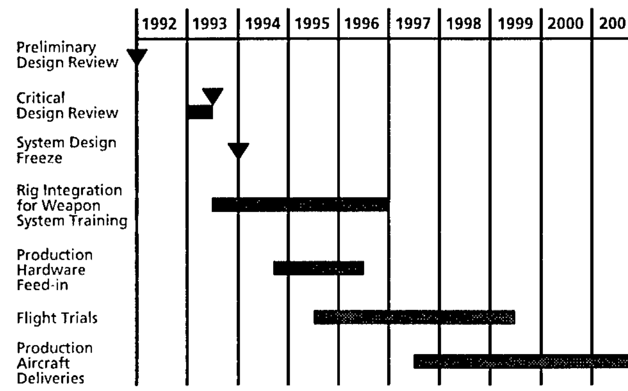


Figure 19: EH 101 Merlin: System Integration Programme

6. TIGER (R. WENNEKERS)

The development of the TIGER helicopter/weapon system is a joint effort at equal parts of Germany and France to meet the requirements for combat support, air-to-air protection, escort, reconnaissance and anti-tank helicopter missions in post cold-war conflict scenarios. The TIGER weapon system concept is founded on a basic helicopter platform and avionic system. From this core three special versions are derived (Figs. 20, 21):

Figure 20

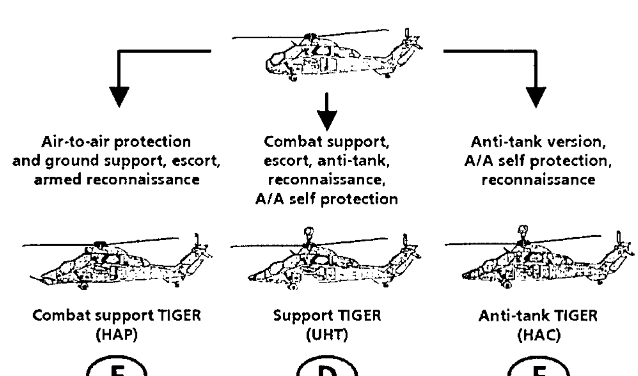


Figure 21: Tiger: Weapon System Concept

– for Germany:

Support TIGER (UHT)

... with mast mounted sight, STINGER ATAM and anti-tank missiles either HOT (wire-guided) or TRIGAT (long range fire and forget) plus unguided rockets and 12.7 mm fixed gun pods.

External fuel tanks for extended range and ferry.

Missions: combat support, escort, anti-tank, reconnaissance, A/A self protection

Feasibility studies to integrate a recoilless MAUSER 30 mm turreted gun are presently under way.

– for France:

Combat Support TIGER (HAP)

... with roof mounted sight, GIAT 30 mm chin mounted cannon, MISTRAL air-to-air missiles (ATAM) and TB 68 mm rockets.

External fuel tanks for ferry.

Missions: Air-to-air protection, ground support, escc:t, armed reconnaissance

Anti-Tank TIGER (HAC)

... with mast mounted sight, MISTRAL ATAM and anti-tank missiles either HOT (wire-guided) or TRIGAT (long range, fire and forget).

External fuel tanks for ferry.

Missions: Anti-tank, A/A self protection, reconnaissance

Common for all TIGER versions is the capability of flight and combat in night and adverse weather conditions. This is provided by a sensor system with IT-and TV-cameras and image intensifier tubes. Presentation of different sensors images and their use by the crew is allocated according to their primary and secondary task for either piloting or weapon operations (Fig. 22). The sight systems in combination with the navigation system (ANAV with GPS), the digital map generator (DMG) and the tactical situation management of the mission system computers as well as the multifunctional displays (MFDs) in the cockpits allow an autonomous operation of the TIGER.

HAP	UHT	HAC
Pilot vision system ❑ Head-up display ❑ Helmet mounted sight ❑ Night-vision goggles	**Pilot vision system** ❑ Thermal imager ❑ Helmet mounted sight/display (2)	**Pilot vision system** ❑ Thermal imager ❑ Helmet mounted sight/display (2)
Gunner visionics ❑ Direct view optics ❑ TV camera ❑ Thermal imager ❑ Laser range finder } *Roof sight* ❑ Helmet mounted sight ❑ Night vision goggles	**Gunner visionics** ❑ TV camera ❑ Thermal imager ❑ Laser range finder ❑ Missile localizer } *MMS*	**Gunner visionics** ❑ TV camera ❑ Thermal imager ❑ Laser range finder ❑ Missile localizer } *MMS*
Armament ❑ 2 X MISTRAL ❑ 30mm turret-mounted gun capability 450 rounds ❑ 2 x 22 unguided rockets ❑ 2 x 12 unguided rockets	**Armament** ❑ 2 X 4 anti-tank missiles HOT or TRIGAT ❑ 2 x 22 unguided rockets ❑ 2 x 12.7 mm gun pod ❑ 2 x 2 A/A missiles STINGER	**Armament** ❑ 2 X 2 MISTRAL ❑ 2 x 4 anti-tank missiles HOT or TRIGAT

Figure 22: Mission Equipment Packages

A 4-axis digital automatic flight control system (AFC), consisting of redundant computers, supports the pilot not only in basic aircraft stabilization but remarkably reduces workload in the cockpit through its auto-pilot modes like attitude hold, IAS hold / capture and hold of altitude and heading, etc. More weapon application specific are the AFCS modes like capture and hold of line-of-sight or gun firing compensation in attitude. These mission system features based on a modern helicopter platform concept, provide a high effectiveness in military operations, supportability ad logistics for the customer.

All sensitive subsystems like the MTR390 engine, the anti-tank armament with TRIGAT launcher and mast mounted sight, the pilot sight unit and additional German avionic options, i.e. the digital map generator (DKG) in combination with HF radio data communications are tested in flight on dedicated helicopters before installation on TIGER.

A suite of ground testing facilities is at the disposal to integrate the different subsystems of basic avionics and mission equipment up to functional chain testing of weapon launchers and sight systems. Important to mention is that the MMI cockpit interfaces and functions for the avionics and weapons systems are developed together with the military user in special working groups.

TIGER has now completed the qualification of the vehicle. Presently the industrial development tests to integrate the different weapon and sight systems are in progress.

7. CONCLUSIONS AND RECOMMENDATIONS

The operational requirements for modern helicopter / weapon systems ask for the installation of a great variety of weapons and equipment packages which may cause substantial problems with respect to helicopter performance, handling qualities, structural mechanics, and vibrations and acoustics.

In the past this integration process was mainly realized with the help of relatively simple engineering methods and tests resulting often in unsatisfactory system performance.

In the Lecture Series AGARD-LS-209 on Helicopter / Weapon System Integration it was demonstrated impressively that only the most advanced analytical and experimental techniques are adequate to quantify and solve the integration conflicts between the host helicopter and the weapon during design, test and evaluation, and operational assessment of the system. In order to minimize the penalties of the weapon system integration, the existing helicopter has to be modified and re-designed, and the new helicopter has to consider early in the design stage the weapon system to be integrated. The concept of concurrent design, whereby all the design specializations are involved simultaneously rather than consecutively, may improve the quality of the design markedly and contribute to the optimal technical solution for the helicopter/weapon interfaces.

Considering the analytical and experimental techniques and data bases available in industry and research organizations it is obvious that the most advanced techniques are often concerned with the clean helicopter only, not including the specific aspects of the integration of external weapon systems. During the industrial development process the improvement of the design tools is not a first priority issue. Therefore, it is recommended to intensity the efforts to incorporate the aspects of weapon integration into the existing advanced design and test procedures, in order to provide the adequate tools, and to make the weapon integration discipline a mature part of the overall design process.

8. REFERENCES

[1] „Integration of Externally Carried Weapon Systems with Military Helicopters", AGARD-AR-247, April 1990.

[2] „Helicopter / Weapon System Integration", AGARD-LS-209, July 1997.

APPLICATIONS OF MODERN MULTIDISCIPLINARY APPROACHES TO THE INTEGRATION OF WEAPONS ON AIRCRAFT

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1. SUMMARY

Modern computational methods are used extensively in the weapon integration process. These methods include, but are not limited to, computational fluid dynamics (CFD), three-dimensional solids modeling, finite element methods, linear and nonlinear structural mechanics, and multi-body dynamic systems analysis. While CFD methods are commonly used for aerodynamic predictions, the magnitude of numerical calculations associated with them often precludes their integration into multidisciplinary design environments. On the other hand, modern aerodynamic analysis procedures based on subsonic and supersonic panel methods are appropriate and have been incorporated into these environments. These procedures are called "engineering methods," and they have been combined with structural analyses, design, flight tests, and dynamic simulation to evaluate weapon/aircraft integration issues. An overview of this process is described and examples from actual weapons integration efforts are discussed. It is shown that these modern engineering methods are accurate and efficient, and can be utilized to complement procedures employed for weapons integration. Conclusions, lessons learned, and recommendations for future efforts are emphasized.

2. INTRODUCTION

Although the approach in this paper is described as being multidisciplinary, the term is not used in the traditional sense of analytical (optimization) techniques. Instead, the approach presented herein is from the perspective of system engineering. It involves a combination of efforts from a variety of people, including aircraft and weapon project engineers, aerodynamic and structural analysts, flight test engineers, data reduction personnel, and simulation engineers. Figure 1 shows a schematic relationship of several engineering disciplines involved in the weapon/aircraft integration process.

Guidelines for weapon/aircraft integration are provided through military specifications, such as MIL-HDBK-244 and MIL-A-8591 (Refs. 1 and 2, respectively). Of these guidelines, MIL-A-8591 has the most direct impact on the integration process. This specification provides background and procedures for meeting the necessary requirements for integration of stores and suspension equipment on aircraft. The work described herein presents some recent efforts in applying procedures from MIL-A-8591 to ensure a satisfactory integration of weapons on aircraft. In this work, it has been necessary to utilize new approaches that incorporate modern aerodynamic and structural analysis tools to accomplish the task. In some cases, new tools were developed specifically to address issues encountered in these weapon/aircraft integration efforts.

Because the approach described herein does not have a long history of application and success, it was necessary to validate the process as part of the effort. Thus, an important part of this work has been to combine analyses and tests to evaluate the accuracy of the approach. This process has provided direction for modifying and upgrading aerodynamic and structural analysis codes, and it has yielded a valuable set of tools for aircraft/weapon integration. The people involved have provided unique and different contributions to the overall success of the work. In the tasks described herein, the multidisciplinary nature of the process has resulted from the collaboration of multiple disciplines.

3. BACKGROUND

3.1 General

In order to understand how this approach evolved, it is helpful to have an understanding of one of the principal documents governing the integration of weapons on aircraft, MIL-A-8591 (Ref. 2). The weapons community in the United States has relied on general specifications, such as MIL-A-8591, to establish aircraft/weapon mechanical and structural interface requirements. From the beginning, this specification has been employed in a "cookbook" fashion. Although it has served well for over 35 years, sometimes it has produced questionable results. In the early years, weapons were typically overdesigned and included many stores that could be utilized on a variety of aircraft without significant modification. The analysis tools were primitive and required many assumptions to cover a variety of unknowns. The ability to accurately define the aerodynamic load environments of a weapon in the presence of an aircraft has been one of the main deficiencies. Correspondingly, the need for more accurate and efficient aerodynamic analysis tools has been an important pursuit. These efforts have resulted in significant progress, and modern methods are available to overcome deficiencies of past approaches.

For many years, the Naval Aeroballistic Advisory Committee (NAAC), a group composed of contractors and U.S. Navy laboratory personnel, recommended that MIL-A-8591 should be changed and made more realistic in its approach. The Joint Ordnance Commanders Group (JOCG),

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Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

Aircraft/Weapon Integration Subgroup, Working Party 12, undertook the task of revising the specification in the early 1980s. The original worst-case load envelope method was retained for fixed-wing aircraft as Procedure A, while a new alternative engineering method or "realistic" approach was introduced as Procedure B. The engineering method approach first appeared in the G revision of the specification in 1983. Along with the introduction of a more realistic approach, MIL-A-8591G was also updated to recognize modern methods of aerodynamic load analysis. A discussion of the essential features of the MIL-A-8591 fixed-wing aircraft load prediction procedures follows.

3.2 MIL-A-8591 Method of Procedure A

Procedure A has been a part of the specification from the beginning and is now referred to as the general method (it is also commonly known as the cookbook method). It is intended to represent a very general, all-encompassing design procedure that covers every possible aircraft. Based on combining an envelope of the worst loading due to inertial effects and the worst loading due to aerodynamic effects, it is intended to create a worst-worst design condition. Unfortunately, this approach results in both over- and underdesign of stores and suspension equipment. Many examples exist where strict application of this approach has led to problems in weapon development programs. One of the main deficiencies with this method is that no flexibility exists to interpret the design conditions and relax them if needed. The inertial load envelopes in Procedure A are specified in a straightforward way, but the aerodynamic load approach is somewhat arbitrary. For example, equations for angles of attack of high performance aircraft are based on the F-111 aircraft flying at high speed and high altitude. When these equations are used to predict angles of attack at lower speeds and altitudes, the results are sometimes grossly inaccurate. It has been long recognized that considerable judgment needs to be applied when using this method, especially for the aerodynamic loading.

3.3 MIL-A-8591 Method of Procedure B

Procedure B is relatively new for MIL-A-8591 and is called the method for specific aircraft. This method was devised to provide a more realistic way of developing weapon design load requirements as well as some flexibility for unusual flight conditions that sometimes arise on specific aircraft. It is based on using actual or predicted aircraft flight performance data to examine the full flight envelope and generate a consistent set of inertial and aerodynamic loads. The method uses well known and accepted engineering analysis procedures. While the appendix of Procedure A incorporates simple methods based on free-stream aerodynamics to obtain worst-case loads, the appendix of Procedure B includes methods that take aircraft interference effects into consideration. These additional methods include various computational procedures (CFD, panel methods, and semi-empirical) as well as wind tunnel flow field surveys. If no other data are available, the simplified worst-case approach of Procedure A is also allowed. According to the specification, any of these aerodynamic load prediction methods may be used to generate aerodynamic loads, provided the contracting authority approves the one selected.

3.4 Development of Modern Aerodynamic Load Procedures

Starting in 1983, the Naval Air Warfare Center Weapons Division (NAWCWPNS) began a systematic effort to adopt the new MIL-A-8591 approach and incorporate new aerodynamic load prediction methods into its analysis procedures. New aerodynamic prediction methods were developed for NAWCWPNS by Nielsen Engineering and Research (NEAR) of Mountain View, California. Under various NAWCWPNS contracts, NEAR personnel have modified, extended, and combined features of several existing aircraft and missile codes previously developed by them. These code developments have been reported in the literature (Refs. 3-8), and a good summary of the current status is given by Dillenius, *et al.*, in Ref. 8. The codes are based on engineering level procedures, which use both panel methods (subsonic and supersonic) and semi-empirical approaches. These computationally efficient codes are very appropriate for generating the volume of aerodynamic data required to support MIL-A-8591 types of analyses. Additionally, these codes produce reasonable first-order accuracy for loads that are consistent with the modeling accuracy of the finite element structural models used in the analyses. The distribution of aerodynamic forces (pressures), which is important to structural analysts, is readily determined from the aerodynamic codes. These forces are easily interpolated into finite element grids for use in existing models.

However, it is not enough that aerodynamic prediction codes are capable of producing the right kind of data. The accuracy of the methods (CFD, engineering methods, or semi-empirical methods) needs to be demonstrated. To this end, NAWCWPNS has conducted an effort to develop the computational procedures and test them through comparisons with actual flight tests. Many people and organizations have collaborated on this effort. It has been called multidisciplinary in this paper to emphasize that the tasks have required efforts from many engineering disciplines.

Applications of these engineering level methods have produced encouraging results so far. For example, in Ref. 4, initial attempts at correlation between predicted and measured loads produced major discrepancies with the new procedures. Subsequent examination of those results led to the conclusion that quasi-static aircraft aeroelastic effects and stalled aerodynamic surfaces needed to be included to properly model the interactions between an aircraft and a wing tip-mounted weapon. Once the necessary modifications were introduced into the computer codes, the results showed closer agreement (Ref. 5). In this instance, conclusions evolved through the concurrent development and application of design tools, the subsequent flight tests, data reduction and analysis, and, finally, the modification and re-application of the tools to validate the basic approach. Close coordination and collaboration between flight test and analysis efforts led to successful modification and application of these new analysis procedures. This is the central theme behind the multidisciplinary approach described in this paper.

3.6 Flight Test Measurements

Because the initial comparisons of predicted and measured results were so different, it was proposed that additional comparisons of analyses and flight test data be made. To that end, captive flight test data were acquired on a variety of aircraft for use in future comparisons. A short summary of these flight test measurement programs is given in this section. The data and results described in this paper have been applied to the AIM-9 Sidewinder missile system, but the methods are not restricted to AIM-9. It has been convenient to use Sidewinder because an instrumented AIM-9 missile, known as the Environmental Test Round (ETR), was readily available for this purpose (see Figure 2). A number of flight test measurement programs have been conducted using the AIM-9 ETR to acquire measured loads and other environmental data. For example, an extensive flight loads measurement program was conducted to characterize the wing-tip environment on the F/A-18 aircraft during 1986 (Refs. 9 and 10). Although the 1986 tests produced mainly acceleration and body strain data, lessons learned from those tests resulted in modifications and additions to the ETR missile for tests conducted in 1989 and 1990 (Refs. 4 and 11). The new additions to this missile were strain gages mounted on the tail fins (also known as wings) to measure the effects of aerodynamic loading during flight. Since the early 1990s, there have been additional tests conducted with the ETR on other aircraft. The US Air Force Test Pilot School (TPS) conducted the most extensive series of tests with the ETR missile during 1993 (Ref. 12) and 1994 (Ref. 13) at Edwards Air Force Base, California. The TPS tests were conducted on F-16 and F-15 aircraft and resulted in the most complete exploration of aircraft flight envelopes to date with an AIM-9 onboard. The most recent series of flight tests conducted with the missile were on the F-16 Multi-Axis Thrust Vectoring (MATV) aircraft[1] during 1996 (Ref. 14). These latter tests included numerous high angle-of-attack maneuvers and other events that were well beyond the capabilities of a standard F-16 aircraft. Although much of these latest data remain to be examined in detail, they have been catalogued and are awaiting future use, as needed, for validating computational procedures and for other purposes.

4. DESCRIPTION OF COMPUTER CODES EMPLOYED IN STUDIES

4.1 Structural Codes

The structural analysis code used in the performance of this work was the well known National Aeronautics and Space Administration (NASA) Structural Analyzer (NASTRAN) (Ref. 15). This code has the capability for analyzing static and dynamic problems, as well as for performing detailed stress and flutter analyses for aircraft and weapons. It is straightforward to build adequate structural models, and techniques for validating structural models are well known. Derivation of appropriate input loads (which are primarily aerodynamic and inertial in this case) is the main problem in performing a MIL-A-8591 type of analysis with NASTRAN. The inertial loads on the store are quasi-static, which are caused by aircraft maneuvers, and dynamic, which are caused by a few transient events. These transient events include catapult takeoffs, arrested landings, and adjacent store ejection.

[1] The F-16 MATV aircraft was a special version of the USAF F-16 Variable In-Flight Stability Test Aircraft (VISTA) that was configured with a General Electric All-Aspect Vectoring Exhaust Nozzle (AVEN).

4.2 Aerodynamic Codes

4.2.1 SUPSAL, SUBSAL

The aerodynamic load prediction codes used in this effort were the SUPSAL (Supersonic Store Air Loads) and SUBSAL (Subsonic Store Air Loads) codes developed by NEAR and described in Refs. 3 and 5, respectively. These panel-method-based codes together provided general capabilities for determining aerodynamic loads over a Mach range up to about $M = 3.0$.

The current versions of these codes have resulted from expanding and enhancing the features contained in the original codes. One of the first modifications made to these codes added the ability to output missile distributed aerodynamic loading and interpolate that loading into NASTRAN finite element models (Ref. 3). The NEAR codes have also been modified to include many kinds of important nonlinear aerodynamic effects. Some of these features include nose chines, nonlinear vortex shedding and tracking, carriage and launch at high angles of attack, and first-order stall models. These added features have come about through the continuing process of comparing analysis and test results.

In order to provide complete sets of loads compatible with MIL-A-8591, the basic codes have recently been extended to also include the capability of predicting aerodynamic loads during aircraft maneuvers, including pitch, yaw, and roll.

4.2.2 STRLNCH

The NEAR Store Launch code, STRLNCH (Ref. 16), is the latest panel-method aircraft aerodynamic prediction code to be developed in this process. STRLNCH has evolved from the original NEAR subsonic and supersonic launch separation analysis codes (Refs. 17 and 18) that have been in use for several years. These original codes have been combined into one code that includes both regimes. The new code, STRLNCH, models a complete three-dimensional aircraft (no planes of symmetry required), so that the full flight environment, including symmetric and nonsymmetric maneuvers, may be evaluated. Additional new features provide for simulation of flow through or around aircraft engine inlets and modeling of high angles of attack at launch. The first working version of the STRLNCH code (subsonic only) was delivered to NAWCWPNS in August 1996. NEAR and NAWCWPNS are currently developing and evaluating a combined subsonic and supersonic version.

As the aircraft aerodynamic prediction methods have been improved, enhancements have also been made in the prediction of store distributed aerodynamic loads. The separate panel method codes, SUBSAL and SUPSAL, have been combined into one code, now named MISDL for Missile Design Loads. This code has been combined with the STRLNCH code to provide missile distributed

aerodynamic loads during both captive carriage and launch. The ability to model the launch sequence and produce aerodynamic loads during a launch is a new feature in STRLNCH. It is also possible to include a simple missile autopilot to control the missile during the launch phase. The analysis can be carried out until the weapon is some finite distance away from the aircraft. To speed up the computations and provide an alternate method for calculating the rapidly varying missile loads during launch, a special, segmented load version of M3HAX (Ref. 19) was developed and adapted to this process. Thus, STRLNCH can be used either with the panel method code, MISDL, or the semi-empirical code, M3HAX, to obtain store loads.

5. EXAMPLES

A few examples from past and present work have been selected to illustrate typical results from the application of these codes. These examples include discussions of test results and are intended to demonstrate the multidisciplinary nature of problems that are encountered during weapon/aircraft integration.

5.1 AIM-9 Sidewinder Forward Hanger Bolt

During the early-to-mid-1980s, structural problems were experienced with the AIM-9M missile on the F/A-18C/D aircraft. It had been determined earlier on the F-16 aircraft that high dynamic loads could be expected during wing-tip carriage of AIM-9 missiles. These high loads occurred while ejecting heavy stores during maneuvers (sometimes referred to as "g-jump"). Even though the weapon was evaluated and pronounced sound for similar load conditions on the F/A-18, it became apparent when the F/A-18 was introduced into the fleet that the missile was not adequate. Failures of forward lugs and attachment bolts began occurring at an increasing rate as flight time with the F/A-18 increased. Initially, it was not apparent whether the problem was due to the missile or the aircraft. McDonnell Aircraft Company (MACAIR), St. Louis, Missouri, indicated that the weapon could experience very high loads (on the order of 50 *g*) during adjacent store ejection. Since these predictions were far outside previous AIM-9 experience, during 1986, NAWCWPNS personnel conducted a flight test program by using the AIM-9 ETR missile (Refs. 9 and 10). Although MACAIR had conducted similar tests, the missile instrumentation was minimal and the data had not been analyzed in a manner that could be used directly by NAWCWPNS engineers. The aircraft engineers were interested only in peak loads, whereas the NAWCWPNS engineers needed to understand the effects of dynamic loads and dynamic responses of the missile.

Upon reviewing the initial data from the flight tests, discrepancies were noted between the MACAIR and NAWCWPNS results, and further investigation was needed to fully understand the problem. Even with the discrepancies, it was apparent that high loads were evident and greatly exceeded those reported in MIL-A-8591G for wing-tip carriage. The first step involved obtaining NASTRAN structural models of the aircraft and missile. An existing beam-type finite element model of the missile and launcher was modified to include the missile launch rail interfaces, the missile hangers, and the forward hanger attachment bolts (Figure 3). Then, a NASTRAN model of the aircraft and AIM-9 missile (Figure 4), which had been developed for flutter analyses by MACAIR, was acquired. The complete aircraft/missile model was exercised to simulate the transient adjacent store ejection events that had been measured (Ref. 20). The computed results were compared to the measured transient acceleration data from the missile, and major discrepancies were immediately noted. After many discussions between analysis and test personnel, the engineers determined that some of the data acquired during the tests had been "clipped" due to insufficient range in the calibration process. An example of one of these comparisons is shown in Figure 5. Unfortunately, much of the clipped data had been selected for analysis, and considerable effort had gone into producing plots before the anomaly was noticed.

Had it not been for the comparison of measured data with the NASTRAN analysis results, the correct solution might have been missed. This error led to changes in data reduction and analysis procedures to preclude it from happening again. Fortunately, once the data reduction errors were corrected and higher ranged transducers were examined, the engineers could show excellent agreement between the measured and predicted acceleration results.

Once the load model was validated with test data, it was possible to develop a retrofit forward hanger bolt that eliminated the failures. This was accomplished by applying newly developed dynamic loads from the NASTRAN missile/launcher model and by determining that a new, stronger bolt was needed to eliminate yielding. Thus, the current hex-head hanger bolt was developed. The NASTRAN analysis model was then coupled with an extensive strength and fatigue test program to qualify the new bolt design.

This example demonstrated how various analytical models could be used effectively, in collaboration with more traditional troubleshooting and testing approaches, to find an effective design solution without resorting to extensive trial and error.

Aerodynamic loading was ignored in this particular analysis, but the results still compared well, indicating that inertial loading dominated in this instance. The successful conclusion of this effort required contributions from both aircraft and weapons personnel. This success encouraged NAWCWPNS personnel to take the next step and continue to introduce more analytical complexity in the form of distributed aerodynamic loading.

5.2 AIM-9 Development Wing

The AIM-9 Development Wing Project was conducted to design a modern wing that would meet AIM-9 mission requirements without the use of thermal protection coating (Ref. 21). Although the wing was not introduced into the fleet, the project demonstrated the use of modern aerodynamic analysis tools and resulted in a wing that was capable of meeting AIM-9 requirements.

A summary of the procedures used to derive design requirements for the AIM-9 wing is given in Ref. 22. The SUBSAL and SUPSAL codes were used to evaluate the distributed aerodynamic loads on the wings, the canard fins, and the missile body while exposed to a variety of flight

conditions on the F/A-18C/D wing tip. In accordance with MIL-A-8591, Procedure B, a matrix of aerodynamic flight conditions was obtained for the F/A-18C/D while it was undergoing two defining flight load maneuvers—a 6-*g* rolling pull-out and a 7.0-*g* symmetric pull-up. This matrix resulted in 18 different load cases to be evaluated. These cases covered the F/A-18 flight envelope, subsonic and supersonic, well.

In order to keep track of the loads on the aerodynamic surfaces of the missile, a tail fin numbering scheme was set up as shown in Figure 6. An example of distributed loads computed with the SUBSAL code for a typical subsonic flight condition (4.0 *g* symmetric pull-up at M = 0.8, altitude = 9508 feet) is shown in Figure 7. This figure also shows how the distributed aerodynamic forces were interpolated into the NASTRAN finite element structural grid.

5.2.1 Comparisons of Measured and Predicted Wing Loads

A series of wing load measurements were made during a special flight test on the F/A-18C/D (Ref. 11). In order to obtain data for direct comparison with predicted results, it was necessary to coordinate the actual maneuvers with the analysis effort. As a result, several symmetric pull-up maneuvers were conducted under various *g* loads. These maneuvers needed to be performed at nearly constant altitude, so as not to complicate the analysis effort. Figure 8 shows the responses of the AIM-9 ETR wing-mounted strain gages during one of the subsonic maneuvers. It can be seen that even during the quasi-steady pull-up, there is oscillation of the missile wing load due to the aircraft wing response. These data were used to obtain the comparisons shown in Figure 9.

Measured strains from the flight tests were converted to resultant loads and compared to overall load predictions from SUBSAL/SUPSAL. Initially, the comparisons were not good, but this led to revisions in the aircraft model that incorporated wing flexure and twist. The results indicated that loads on the missile wings were highly dependent on the location of vortices being shed from the aircraft wing tip. This location was highly influenced by the aircraft wing dynamics. These results led to the conclusion that aircraft aeroelastic effects are very important in determining the correct loads on wing tip-carried stores.

Because the strain gage readings were subject to considerable temperature drift, it was not possible to obtain an absolute calibration for the wing load. Instead, the aerodynamic loads were analyzed slightly before and during the maneuver, because the thermal effects were minimal in that short time span. Thus, it was possible to obtain the wing load increments due to the maneuver and compare them with the predicted load increments. As can be seen in Figures 9c and 9d, the predicted and measured load increments compared well for this particular subsonic maneuver. Other comparisons were not as good, but the calculations still produced loads with the right order of magnitude.

Acquisition of these flight test results required considerable collaboration between aerodynamics, structures, flight test, and missile instrumentation personnel involved in the tests. The synergism of the collaboration between various participants resulted in substantial contributions to this effort. These results continued to expand the author's confidence in the ability of engineering methods to be useful tools in the weapon/aircraft integration process.

5.2.2 NASTRAN Finite Element Predictions

Distributed wing loads from the SUBSAL/SUPSAL analyses were subsequently applied to a detailed NASTRAN finite element model of the wing. The results were then used to model the measured flight load stresses in the wing and aid in interpreting the flight test data. The NASTRAN model was also used to interpret test results from laboratory qualification tests of the wing, thus enabling an understanding of the differences in stress distributions between the laboratory loads and the flight test loads. In the past, considerable guess work and assumptions would have been necessary to arrive at such conclusions about wing loading.

The NASTRAN model made it possible to gain understanding that led to a better definition of design requirements for the AIM-9 wing. The ability to perform accurate post-test evaluations through the use of structural models also greatly reduced the uncertainty about flight test data. The aerodynamic loads developed with the SUBSAL and SUPSAL codes played an important role in arriving at a suitable modern wing design.

5.3 AIM-9 Missile and LAU-7 Launcher Design Loads

The aerodynamic loads developed with SUBSAL and SUPSAL were also used to update the AIM-9 missile design loads (Ref. 23) and LAU-7 launcher loads (Ref. 24). One interesting result from this load update effort provided an explanation for why the AIM-9 aft hanger and the LAU-7 launcher have experienced increased wear when carried on the F/A-18 wing tip. The missile wings experience large forces imposed by the vortex shed from the aircraft wing tip. This vortex wraps around the missile body causing a rather large roll torque to be applied (dynamically) to the aft end of the missile through the wings. These forces, in turn, impose a dynamic roll torque on the launcher through the aft missile hanger. As can be seen in Figure 3, the aft section of the launcher body must support the roll moment acting on the launcher. Because the launcher does not have good torsion stiffness in that region, it is unable to sustain the loads well. Because the rolling moment is dynamic and changes strength as the aircraft maneuvers, it produces some rather severe dynamic loading for the aft end of the launcher. This dynamic vortex load only occurs at the wing tip location on the aircraft. Similar effects have not been reported in other locations.

This example shows how models developed for one specific problem can lead to a better understanding and solutions for related problems. Developing the necessary design data for this wing produced additional information that provided an explanation for problems experienced on the launcher. The normal troubleshooting approach would probably not have reached this conclusion.

5.4 AIM-9 Launch Simulation

The final example presents results for simulation of a fairly high angle of attack launch of an AIM-9 missile from the wing tip of an F/A-18 aircraft. The comparison of a predicted flight trajectory with a photograph of an AIM-9 that was launched under similar conditions is shown in Figure 10. This comparison shows that the dynamic response of the missile was predicted well by the STRLNCH code. Since the STRLNCH code was developed expressly for determining missile aerodynamic loads during carriage and launch from a maneuvering aircraft, these results gave confidence in its application. It is expected that loads from subsequent STRLNCH predictions will be used in structural analysis efforts for both aircraft and missiles to evaluate the effects of aircraft maneuvers. The results from these analyses may also be used to examine the dynamic nature of the aerodynamic loading, as well as to model the missile trajectory behavior.

6. WHAT IS THE NEXT STEP?

The next generation of missiles will require autopilots for guidance through the transients that occur during launches, such as the one described above. It will be necessary to include more fidelity in the design of these autopilots in order to examine that portion of the flight envelope. The aircraft may be maneuvering rapidly and flying at high angles of attack. NAWCWPNS has made an initial step toward developing a very complete multidisciplinary simulation to model and analyze such an event (Ref. 25). This simulation is called the Three Body, Six Degree of Freedom (3BOD6DOF) Simulation. It is designed to model the launching aircraft, the missile, and the target aircraft, all simultaneously with six degrees of freedom. The simulation utilizes a commercially available computer code, MATRIX-X(c), developed by Integrated Systems, Inc., (ISI) of Santa Clara, California. ISI developed an initial version of the simulation for NAWCWPNS. This simulation employs a graphical user interface (GUI) to assemble the model in block diagram form. A pictorial representation of the top-level block diagram of the 3BOD6DOF simulation is shown in Figure 11.

One of the essential features of this simulation is that it utilizes the inherent capability of the MATRIX-X(c) package to include embedded analysis procedures. Thus, the simulation will include a special subsonic version of the STRLNCH code, the Subsonic Parent Aircraft Flow Field (SBPAFL) code (Ref. 26), to model local aircraft flow field effects during maneuvering launches. The missile aerodynamics are calculated on-the-fly using a special embedded version of M3HAX that computes missile forces in the nonuniform flow created by the aircraft interference. Because the simulation is installed on a workstation, it was necessary that the aerodynamic prediction portions of the analysis be computationally efficient, as well as accurate. The SBPAFL and M3HAX codes satisfy this need and result in a very usable, multidisciplinary simulation.

Personnel at NAWCWPNS have not utilized the full simulation, yet. When the embedded missile aerodynamic code, M3HAX, was used, it has produced reasonable run times on a relatively slow (by today's standards) Silicon Graphics workstation. Efforts are currently underway to complete the installation and verification of both embedded aerodynamic prediction codes, M3HAX and SBPAFL. It is expected that this simulation will be used extensively with the next generation of missile systems. As confidence in the accuracy of the embedded aerodynamic prediction codes grows, NAWCWPNS personnel will begin to examine the use of this simulation for missile autopilot design. It is expected that the multidisciplinary nature of the simulation will also continue to be expanded. It may be used not only for missile trajectory and autopilot evaluations but also for developing missile design loads during maneuvering launches and other conditions.

7. CONCLUSIONS

Modern aerodynamic prediction codes based on engineering methods have been shown to work well. With these tools designers and engineers can move away from cookbook methods and begin to develop a better understanding of aircraft and weapon integration characteristics. The tools are robust and computationally efficient, and they can be employed in routine, everyday design situations. Comparisons of predicted and measured results have shown good correlation for a variety of typical aircraft/weapon integration problems.

It is now possible to include more realistic modeling of aerodynamic forces in a number of important design applications, including structural analyses and missile simulations. There are many other applications that have yet to be explored with these tools. It is expected that, in the future, there will be more attempts to combine applications and link them in a multidisciplinary fashion. This is likely to become the norm in future design efforts.

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9. ACKNOWLEDGMENTS

The author wishes to acknowledge the capable assistance of personnel from Nielsen Engineering and Research, Inc., Mountain View, California, and Integrated Systems, Inc., Santa Clara, California, in the preparation of this work.

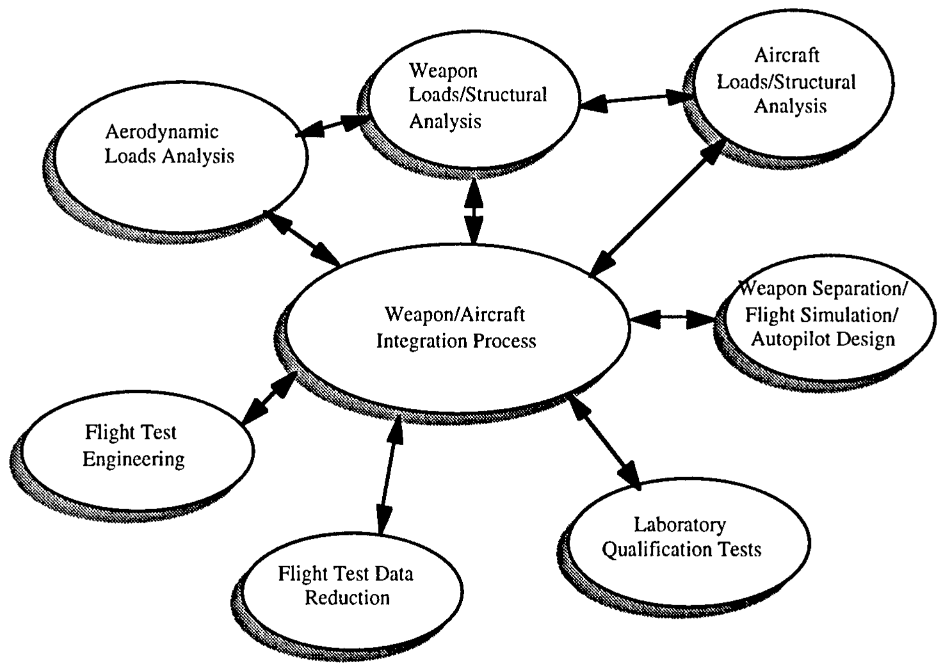
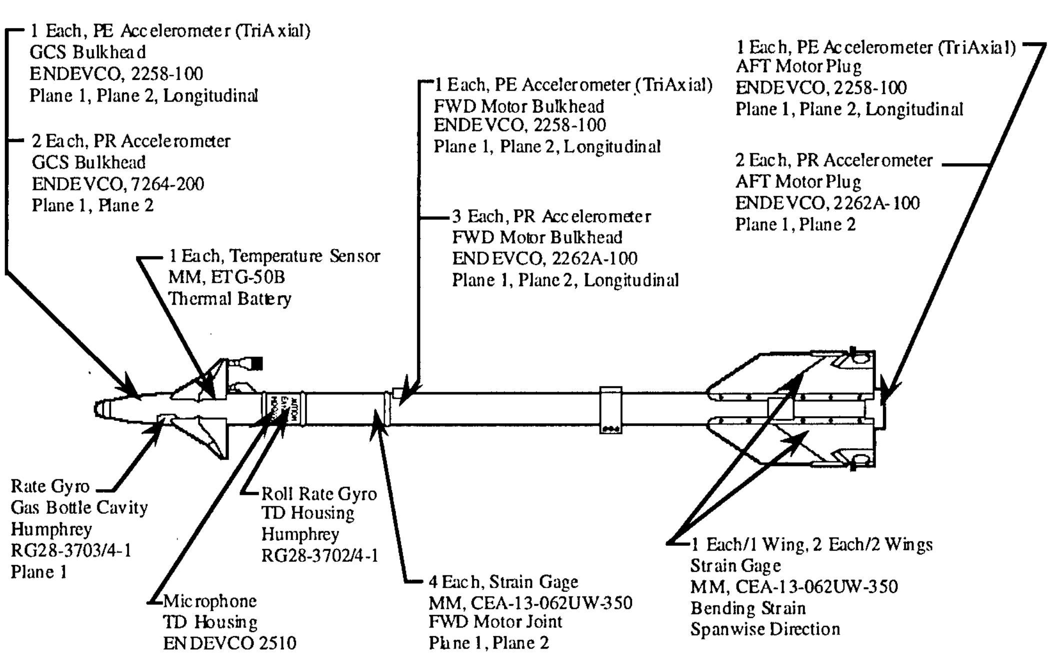


Figure 1. Schematic Showing Various Disciplines Involved in Weapon Integration Process.



Note: Plane 2 is Through the Missile Hangers (Aircraft Horizontal for F/A-18 Wingtip Installation)
Plane 1 is Perpendicular to Plane 2 (Aircraft Vertical for F/A-18 Wingtip Installation)

Figure 2. Schematic of AIM-9 Environmental Test Round Instrumentation.

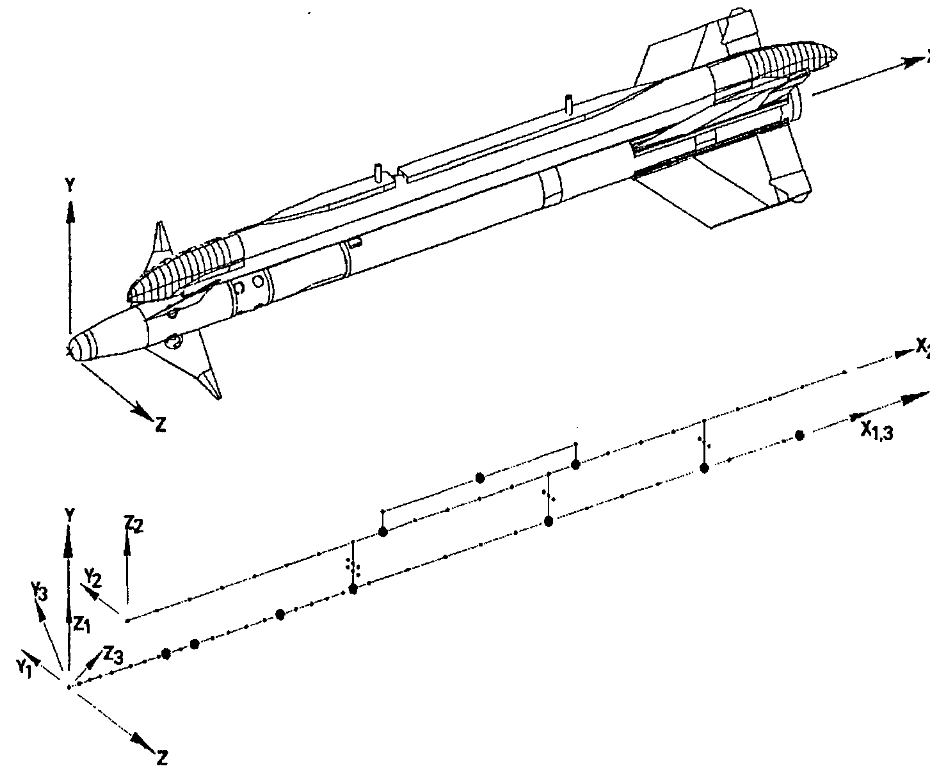


Figure 3. NASTRAN Captive Carriage Model of AIM-9/LAU-7.

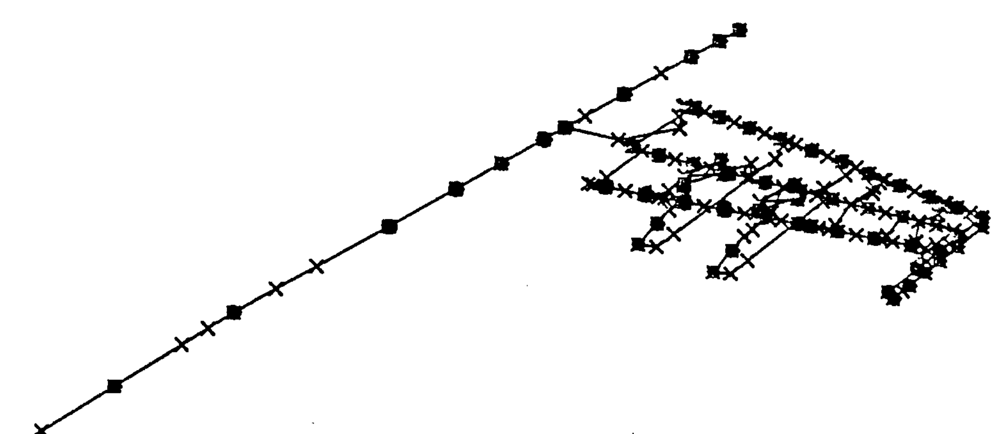


Figure 4. NASTRAN Model of F/A-18 Aircraft.

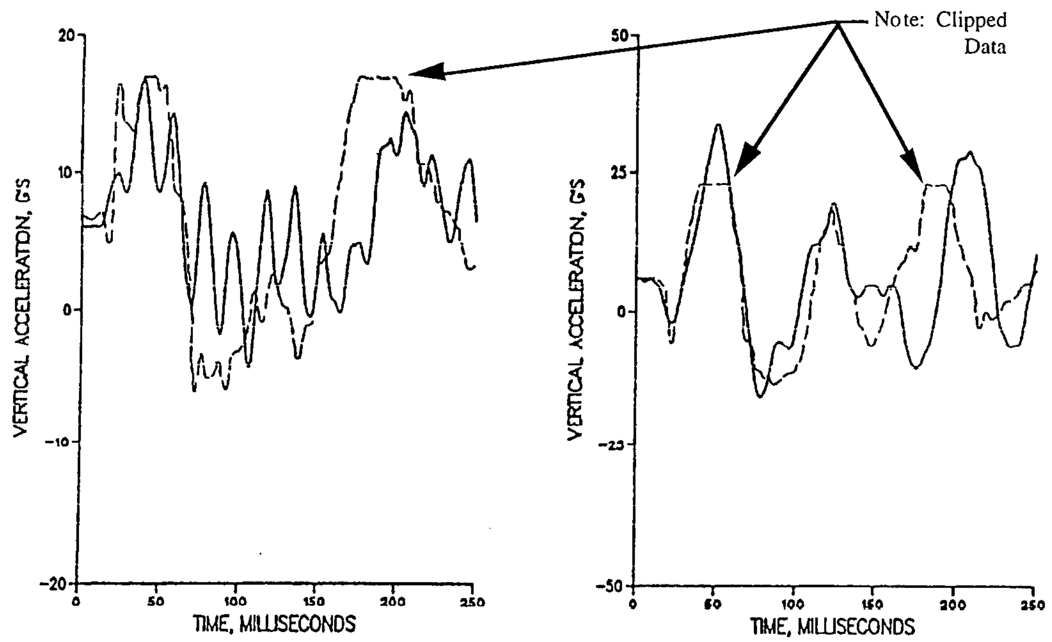


Figure 5. Computed (Solid) vs. Test (Dashed) Missile Acceleration Response at Forward (Left) and Aft (Right) Attachment Points Following Ejection of Two Mk 84 Bombs (6.0 g Base Acceleration).

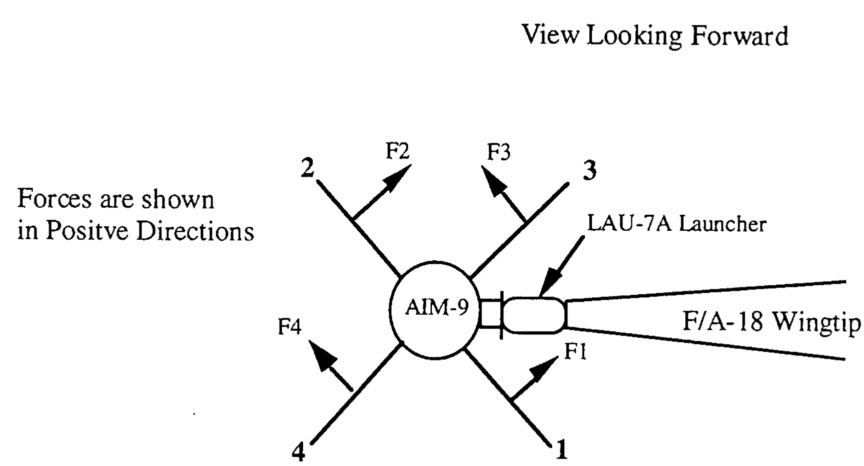


Figure 6. AIM-9 Tail Fin (Wing) Nomenclature.

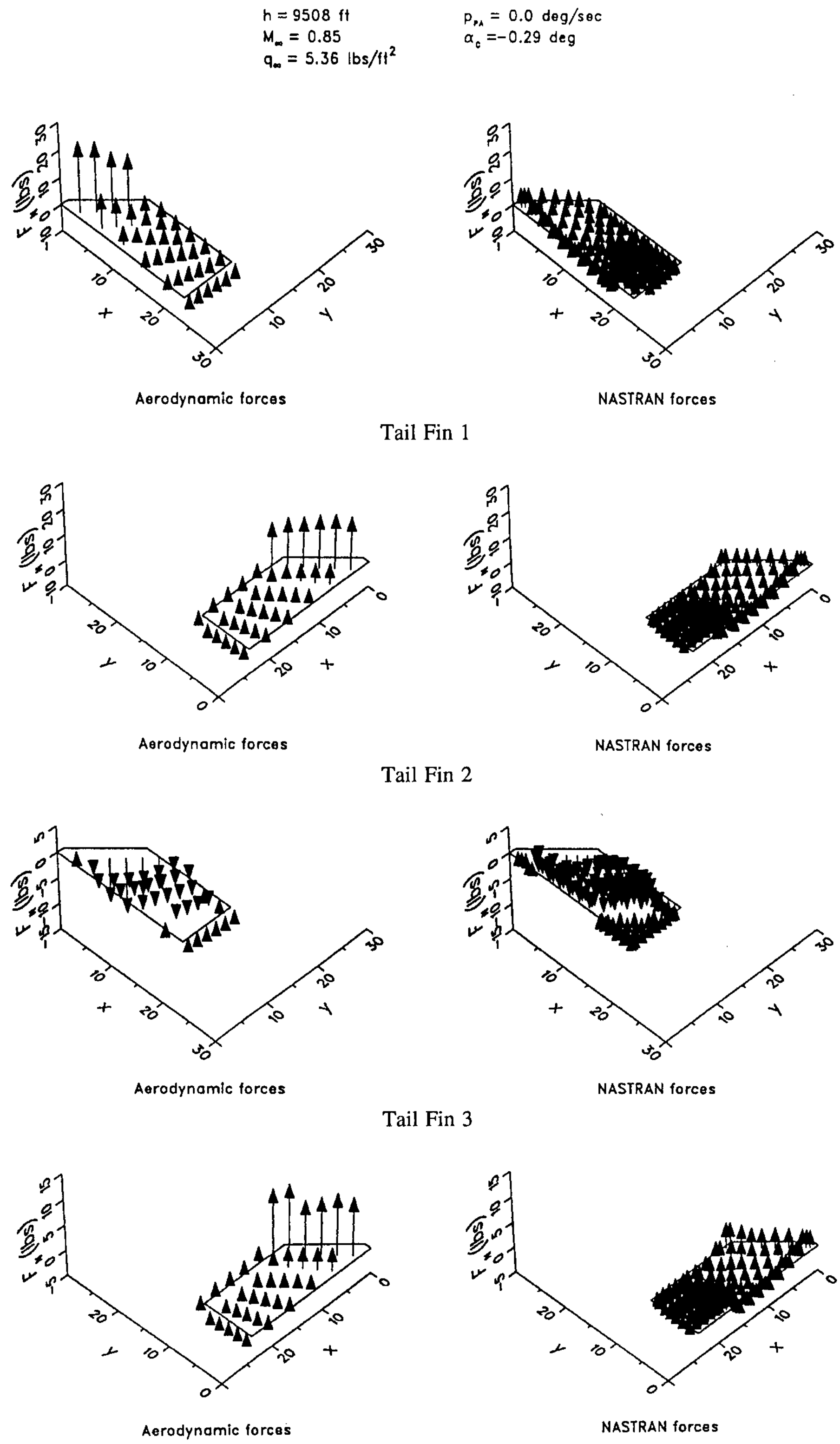


Figure 7. Examples of Computed Aerodynamic Loading on AIM-9 Tail Fins for 4.0 *g* Symmetric Pull-up at M = 0.85, Altitude = 9508 ft.

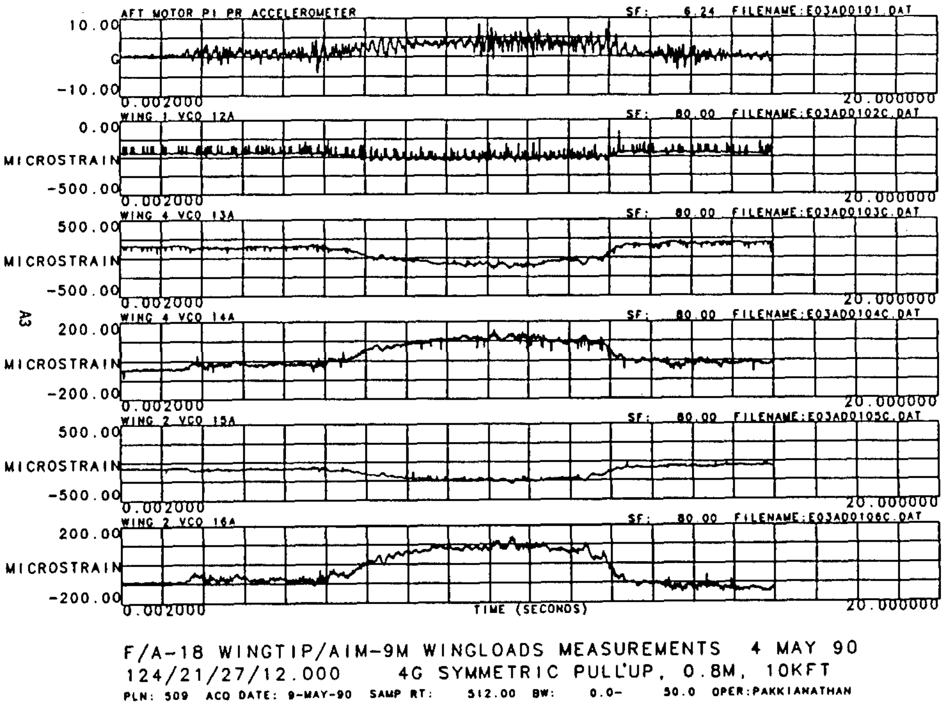


Figure 8. Examples of Strain Gage Output on AIM-9 Tail Fins (Wings) for 4.0 *g* Symmetric Pull-up at M = 0.8, Altitude = 10,000 ft.

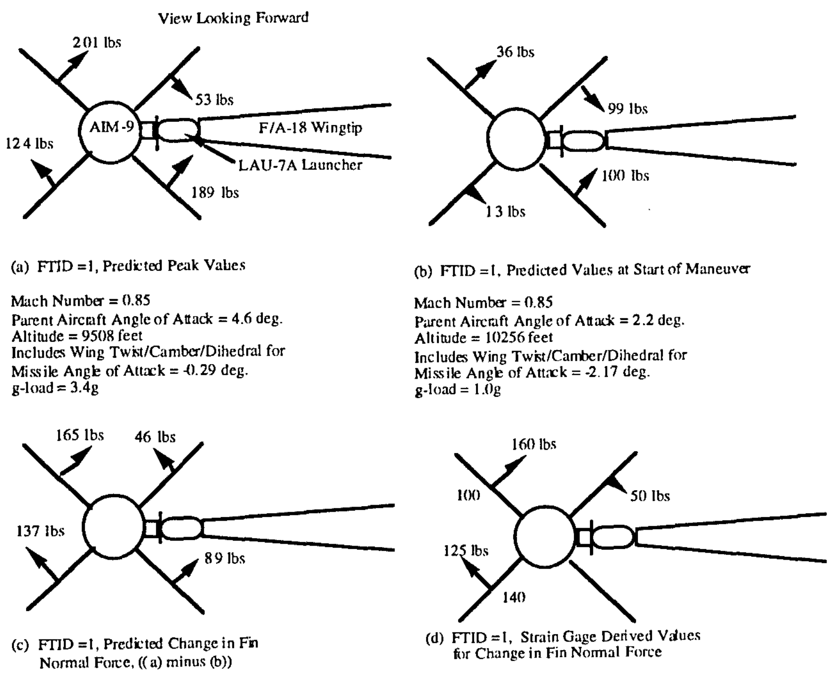


Figure 9. Comparison of Predicted Tail Fin Loads with Flight Test Data.

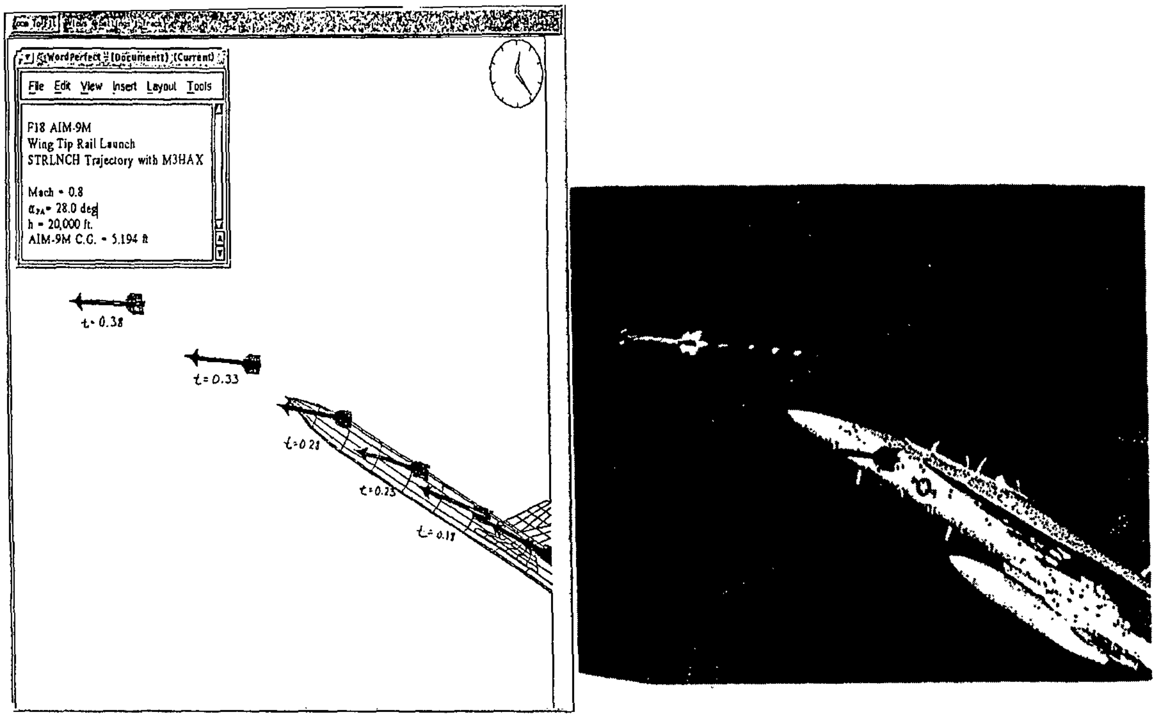


Figure 10. Comparison of STRLNCH Results with Actual AIM-9 High Angle Launch from F/A-18 Wing Tip.

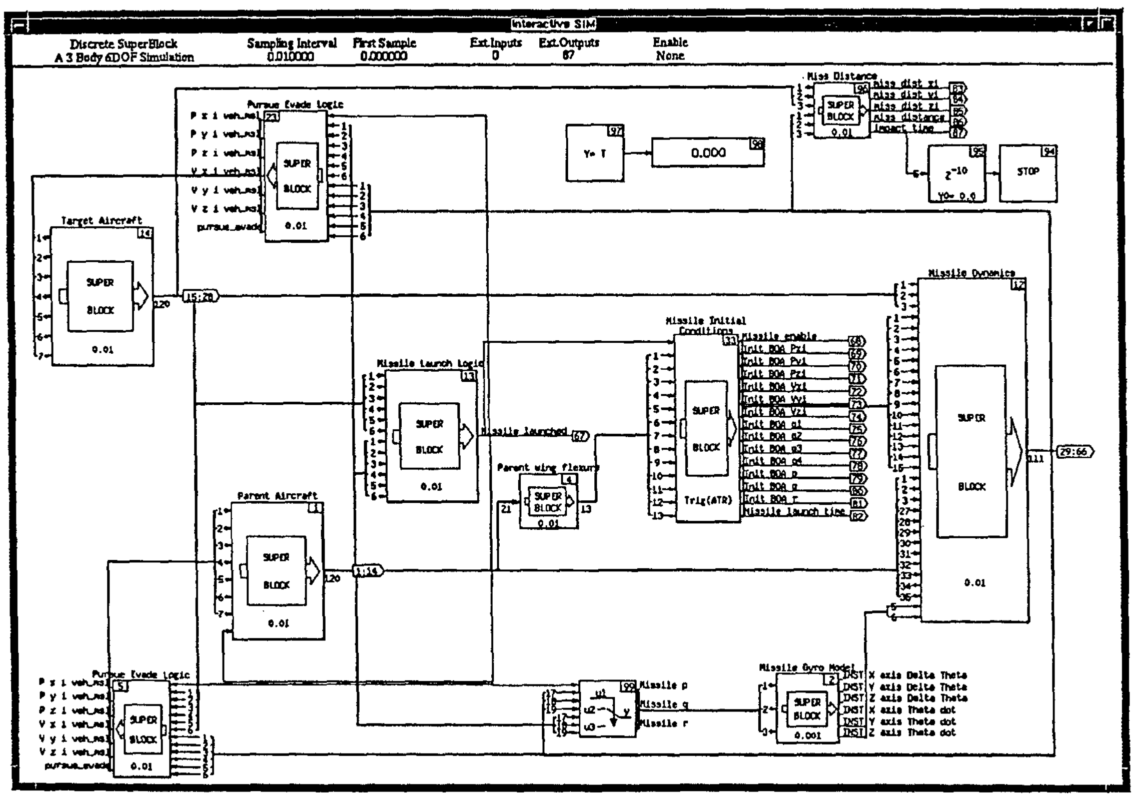


Figure 11. Top Level Block Diagram of MATRIX-X(c) 3BOD6DOF Simulation.

COMMENT MAITRISER LA COMPLEXITE CROISSANTE DE L'INTEGRATION DES ARMEMENTS A UN AVION DE COMBAT ?

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1 RESUME

Depuis le milieu des années 80, l'intégration d'une arme à un porteur est devenue de plus en plus complexe, entraînant une augmentation des cycles et des coûts supportée in fine par l'utilisateur.

Ce phénomène s'est particulièrement accentué les dernières années. Il résulte de l'accroissement du nombre et de la nature des interactions entre ces deux parties d'une part et des contraintes budgétaires d'autre part. Dans ce contexte, il est donc nécessaire de faire évoluer le processus actuel de définition et de développement de l'ensemble « avion + arme ».

Au travers de l'exemple des armes Air/Surface, cette conférence se propose de présenter les évolutions de ce processus préconisées par Dassault Aviation en vue de maîtriser cette complexité croissante.

2 INTRODUCTION

L'évolution du contexte géostratégique (émergence rapide de foyers de crise dans des environnements de plus en plus complexe, ...), du contexte technologique (technologie de plus en plus performante accessible à un plus grand nombre) et du contexte médiatique (effet « CNN ») constatée de puis ces dernières années, a entraîné une modification des missions et des situations dans lesquelles les Forces Armées seraient amenées à intervenir, mais aussi une augmentation des contraintes imposées au couple avion « avion + arme ».

Ces nouvelles contraintes, principalement exprimées en terme de mise en œuvre, de vulnérabilité, de discrétion ou encore de maîtrise des effets collatéraux entraînent un accroissement des interactions entre la définition de l'arme et celle de l'avion et des systèmes principal et de soutien.

Ces couplages forts ont pour conséquence une augmentation de la complexité des travaux d'intégration des armements, ayant pour conséquence l'accroissement des délais et des coûts que l'utilisateur final doit supporter. C'est pourquoi dans un contexte budgétaire toujours plus contraint, il apparaît nécessaire de faire évoluer le processus actuel afin de trouver au plus tôt les termes d'échanges « Avion ⇔ Arme » permettant de dégager les compromis et de définir un ensemble homogène, compatible de ce nouveau contexte.

3 L'EVOLUTION DES CONTRAINTES

Les contraintes relatives à l'intégration d'un armement étaient, il y a une vingtaine d'années, beaucoup plus restreintes.

Ainsi quand il fallait considérer l'intégration d'une bombe lisse les aspects vulnérabilité du couple « avion + arme » ou encore maîtrise des risques collatéraux ne faisaient pas partie de l'expression de besoin des utilisateurs. Celle –ci se limitait principalement à une description des configurations d'emport et du profil d'attaque souhaité. Aujourd'hui, cette expression de besoin est devenue plus complexe en incluant notamment des contraintes plutôt à caractère opérationnel comme :

◊ Sur les taux de survivabilité et de discrétion sur le couple « avion + arme » (liées notamment au perfectionnement des défenses amène des contraintes)

◊ Sur la maîtrise des effets collatéraux et sur la restitution de mission pour participer à la preuve de cette maîtrise

◊ Sur la simplicité de mise en œuvre de l'ensemble « avion + arme » (automatisation / transparence de certaines actions pilote ou états de l'arme)

ou plutôt à caractère technique comme :

◊ Sur la protection des données sensibles spécifiques à la mission

La réponse à l'ensemble de ces contraintes qui se fait au travers des définitions de l'arme et de l'avion, est à l'origine de l'augmentation du volume des interactions "avion ↔ arme".

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

4 DES INTERACTIONS DE PLUS EN PLUS NOMBREUSES : UN PROCESSUS ACTUEL DEVANT EVOLUER

Après avoir illustré au travers de l'exemple des armements Air/Surface l'augmentation du nombre et de la complexité des interactions entre la définition de l'avion et celles des armes, cette partie de l'exposé conclura sur la nécessité de faire évoluer le processus d'intégration actuel.

Cette analyse s'appuie sur la présentation successive :

◊ D'un découpage en étapes d'une mission Air/Surface,

◊ Des interactions entre les définitions de l'avion et de l'arme au cours de certaines de ces étapes

◊ Des conséquences de la non prise en compte de ces interactions en terme de coûts et délais, performances et sécurité sur la définition du système global.

4.1 Phases d'une mission Air/Surface

Les interactions entre une arme et un avion ne se limitent plus aux seuls aspects de mise en place sous l'avion, de désignation de l'objectif et de séquence de tir. C'est pourquoi, afin de mieux estimer le « poids » d'une interaction dans la réalisation d'une mission, il est nécessaire de découper plus finement cette dernière.

Il est possible de décomposer une mission Air/Surface en 7 étapes successives : chacune de ces étapes pouvant elle-même se décomposer en différentes phases. Une courte description de ces étapes est donnée ci-après.

1. <u>Préparation de la mission "avion + arme"</u>

   Cette phase comprend toutes les actions permettant de générer les bases de données avion et arme nécessaires à la réalisation de la ou des missions demandées dans une structure et un volume compatible de leur embarquabilité

2. <u>Mise en œuvre "avion + arme" au sol / tenue d'alerte</u>

   Cette phase comprend toutes les actions permettant de disposer d'un avion et d'armes montées à poste, prêts au décollage ou au catapultage

3. <u>Départ de l'avion</u>

   Cette phase correspond au décollage ou au catapultage de l'avion (lâcher des freins → rentrée du train)

4. <u>Mise en œuvre "avion + arme" en vol jusqu'au tir</u>

   a. Navigation vers la zone d'opération / hors de la zone d'opération

      Cette phase comprend pour la partie "aller" de la mission, toutes les actions se déroulant entre la rentrée du train et la sélection par le pilote de la fonction d'arme et pour la partie "retour" de la mission, l'ensemble des actions se déroulant entre la désélection de cette fonction et la sortie du train

   b. Mise en œuvre de la conduite de tir / préparation de l'arme

      Cette phase comprend toutes les actions permettant d'initialiser le système de l'avion et des armes avec les éléments "statiques" de la mission à réaliser. Cette phase qui débute à la sélection de la fonction par l'équipage se termine au début de la mise en œuvre opérationnelle des armes

   c. Acquisition / désignation de l'objectif

      Cette phase comprend toutes les actions permettant d'acquérir et/ou de modifier les données relatives à l'objectif de la mission. Cette phase se déroule en parallèle de la précédente

   d. Mise en œuvre opérationnelle de l'arme

      Cette phase comprend toutes les actions permettant d'initialiser le système de l'avion et des armes avec les éléments "dynamiques" de la mission à réaliser (alignement des références inertielles des armes, ...). Cette phase se termine lors de la séparation des armes. Elle peut comprendre des parties irréversibles selon les armes.

   e. Mise en position de tir

      Cette phase comprend toutes les actions permettant d'amener l'avion dans la partie de l'espace et dans les conditions cinématiques et aérodynamiques compatibles d'une séparation permettant à l'arme d'atteindre son objectif. Cette phase se déroule en parallèle de la précédente et se termine à la séparation effective des armes

   f. Séquence de tir

      Cette phase comprend toutes les actions et tout le dialogue avion/arme se déroulant entre l 'appui sur le poussoir de tir et la séparation effective des armes. Elle se déroule en parallèle de la précédente.

   g. Séparation avion / arme

      Cette phase comprend toutes les actions avion et armes se déroulant depuis la séparation effective de l'arme jusqu'à la sortie du champ aérodynamique avion

5. <u>Mise en œuvre "avion + arme" en vol après tir</u>

   a. Vol libre de l'arme sans liaison avec l'avion

Cette phase correspond à la partie de la mission où l'arme en vol n'a aucune liaison avec l'avion

b. Mise à jour de la désignation de l'objectif lors du vol libre de l'arme

Cette phase correspond à la partie de la mission où l'arme en vol est en relation avec l'avion (de façon uni ou bidirectionnelle) et où l'équipage a la possibilité de mettre à jour via cette liaison les données caractérisant l'objectif à traiter par l'arme

c. Recueil de la preuve de frappe lors du vol libre de l'arme

Cette phase correspond à la partie de la mission où l'arme en vol est en relation avec l'avion pour lui transmettre (ponctuellement ou de façon continue) une preuve de l'endroit impacté. Cette phase se superpose à tout ou partie de la phase précédente

6. <u>Retour de l'avion</u>

Cette phase correspond à l'atterrissage ou à l'apportage de l'avion (sortie du train → arrêt au parking)

7. <u>Restitution de mission / remise en condition</u>

a. Restitution de mission

Cette phase correspond à l'ensemble des actions permettant de rejouer tout ou partie de la mission après le retour de l'avion

b. Maintenance et remise à condition

Cette phase correspond à l'ensemble des actions avion et arme permettant après retour de l'avion de disposer d'un avion et d'armes à poste, prêts au décollage ou au catapultage

On peut noter que selon l'armement Air/Surface considéré (Bombes lisse, armement guidé laser, armement à imagerie avec ou sans data-link, armement stand-off, armement antinavire, ...), certaines de ces étapes peuvent ne pas exister ou exister dans une forme très simplifiée.

4.2 Interactions des définitions avion et arme

La nature des interactions dépend du type d'armement considéré ; une analyse des différentes phases de missions dans le cas d'une arme possédant une navigation inertie hybridée GPS et un guidage terminal à imagerie avec data-link « avion ⇔ arme » amène à recenser environ 250 situations d'interaction potentielles entre la définition de l'avion et celle de l'arme, certaines situations étant identifiées au cours de plusieurs phases.

Les tables suivantes présentent les résultats de cette analyse sur 3 d'entre elles. Au sein de chaque phase de mission, les interactions (en typographie « normale » et précédé d'un " ◊") sont regroupées par "origine de contraintes"(en typographie « gras souligné » et précédé d'un "•").

Afin de montrer l'évolution de la nature et du nombre des interactions par rapport à un armement plus ancien (par exemple de type GBU 12), la typographie en italique est utilisée pour identifier les interactions existant pour ce dernier.

- **<u>Préparation "système" arme</u>**

◊ options de fonctionnement de l'arme
◊ nature et volume des données à transférer de l'avion vers l'arme
◊ besoin d'un autotest
◊ durée de la phase de préparation de l'arme
◊ nature et volume des données transmises par l'arme

- **<u>Compatibilité EM</u>**

◊ Caractéristiques des Emetteurs/Récepteurs de l'avion
◊ caractéristiques des émetteurs/récepteurs mis en oeuvre lors de la préparation de l'arme

- **<u>Sécurité</u>**

◊ objectif de sécurité lors de la préparation de l'arme

- **<u>Contraintes "système" avion</u>**

◊ caractéristiques des réseaux numériques et vidéo de l'avion
◊ *caractéristiques de l'interface homme/système*

- **<u>Contraintes Conduite De Tir</u>**

◊ *allocation système (Vmémoire, Pcalcul, Nréticules, ...) de la Conduite De Tir*
◊ *modes de fonctionnement de la Conduite De Tir (modes dégradés,...)*

- **<u>Caractéristiques électriques "avion"</u>**

◊ capacité du réseau électrique
◊ connectique "avion + pylône"

- **<u>Caractéristiques électriques "arme"</u>**

◊ besoin en alimentation AC, DC
◊ durée maximale de MST autorisée en vol porté

- **<u>Concept d'emploi du système avion</u>**

◊ *superposition de fonctions*
◊ *gestion des ressources*

<u>TABLE 1</u>

« Interactions lors de la phase de mise en œuvre de la conduite de tir / préparation de l'arme »

- **<u>Initialisation "système" arme</u>**

◊ nature et caractéristiques des données nécessaires à l'initialisation arme (alignement,...)
◊ gabarit de vibration compatible de l'alignement
◊ durée de la convergence de la méthode d'alignement/type de manoeuvre
◊ durée de validité de l'alignement
◊ nature et durée des phases réversible et irréversible de la mise en oeuvre arme

• **<u>Sécurité lors de la phase de mise en oeuvre opérationnelle</u>**
◊ événements redoutés/critiques arme - Besoin en sécurisation des échanges
◊ objectifs de sécurité lors de la mise en oeuvre opérationnelle de l'arme
◊ architecture matérielle/fonctionnelle/logicielle arme
◊ architecture matérielle/fonctionnelle/logicielle avion
◊ objectifs de sécurité avion
• **<u>Caractéristiques "système" avion</u>**
◊ caractéristiques des données du vecteur d'état avion (nature, performances, retard,...)
◊ caractéristiques du réseau numérique
◊ définition des manoeuvres couplables
• **<u>Caractéristiques mécaniques avion</u>**
◊ souplesse avion au point d'emport + performances de la modélisation embarquée
• **<u>Caractéristiques électriques avion</u>**
◊ capacité du réseau électrique avion
◊ connectique
• **<u>Caractéristiques "mécaniques" arme</u>**
◊ domaine de mise en oeuvre de certains éléments de l'arme
• **<u>Caractéristiques "électriques" arme</u>**
◊ besoin en alimentation électrique
◊ connectique

<u>TABLE 2</u>

« Interactions lors de la phase de mise en œuvre opérationnelle de l'arme »

• **<u>Chronogramme de séparation</u>**
◊ *trajectoire arme après séparation (typiquement les 10 premières secondes)*
• **<u>Caractéristiques "mécanique et aérodynamique" avion</u>**
◊ *définition des éjecteurs*
◊ *caractéristiques du champ proche avion perturbé par l'arme*
• **<u>Caractéristiques "mécaniques" arme</u>**
◊ caractéristiques du jet de l'arme
• **<u>Sécurité lors de la phase de séparation</u>**
◊ besoin en pilotage de l'arme après séparation
◊ définition des manoeuvres couplables
◊ définition du domaine accessible par l'avion
• **<u>Caractéristiques aérodynamiques arme</u>**
◊ caractéristiques arme inerte
◊ caractéristiques arme "non inerte"

<u>TABLE 3</u>

« Interactions lors de la phase de séparation avion/arme »

Ces tables illustrent l'évolution des interactions entre les deux types d'armement ; celles-ci sont simples et en nombre réduit pour la GBU 12 alors qu'elles mettent en œuvre plusieurs domaines (système, aéromécanique, ...) et sont plus nombreuses dans l'exemple d'armement à imagerie considéré.

Il faut noter par ailleurs que l'importance des ces interactions est pondérée par le besoin opérationnel exprimé par l'utilisateur ; les tables suivantes montrent quelles phases de mission sont potentiellement concernées par 3 thèmes qu'il est possible de retrouver dans une expression de besoin faite par l'utilisateur :

• Préparation de mission « avion + arme »
• Mise en œuvre « avion + arme » au sol / tenue d'alerte
• Navigation vers la zone d'opération
• Mise en œuvre de la conduite de tir / préparation de l'arme
• Acquisition / désignation de l'objectif
• Mise en œuvre opérationnelle de l'arme
• Mise en position de tir
• Séquence de tir
• Séparation avion / arme
• Vol libre de l'arme
• Mise à jour de la désignation d'objectif
• Recueil de la preuve de frappe

<u>TABLE 4</u>

« Influence d'une expression de besoin en terme de maîtrise des effet collatéraux »

• Navigation vers/hors de la zone d'opération
• Acquisition/désignation de l'objectif
• Mise en position de tir
• Séparation avion/arme

<u>TABLE 5</u>

« Influence d'une expression de besoin en terme de discrétion de la passe de tir »

• Préparation de mission « avion + arme »
• Mise en œuvre de la conduite de tir / préparation de l'arme
• Acquisition / désignation de l'objectif
• Mise en œuvre opérationnelle de l'arme
• Séparation avion / arme
• Vol libre de l'arme

<u>TABLE 6</u>

« Influence d'une expression de besoin en terme de précision au but »

4.3 Conséquences des interactions

Si elles ne sont pas considérées en temps et en heure, certaines interactions peuvent avoir des conséquences importantes sur le projet global « avion + arme » soit en terme de délais, soit en terme de coût ou d'inadéquation au besoin opérationnel ou encore en terme de sécurité.

Si nous considérons notre exemple d'armement à imagerie, trois interactions peuvent illustrer ces propos :

◊ Un mauvais dimensionnement relatif des capacités de localisation et de guidage terminal de cet armement et des capacités de désignation d'objectif peuvent amener à remettre en cause un ou plusieurs de ces éléments afin de pouvoir satisfaire au besoin exprimé par l'utilisateur ou à diminuer les concepts d'utilisation de cet armement

◊ Un mauvaise adéquation du comportement de l'arme lors de la phase de séparation aux objectifs de sécurité demandés par l'utilisateur peut amener à remettre en cause les spécifications du pilote de l'arme et/ou des paramètres transmis par l'avion juste avant tir ou à diminuer le domaine d'emploi de l'armement

◊ Une mauvaise adéquation des interfaces électromagnétiques avion/arme peut amener à remettre en cause la définition de certains émetteurs et/ou récepteurs de l'avion et/ou de l'arme ou à diminuer les concepts d'utilisation de cet armement

4.4 Un processus actuel devant évoluer

Les paragraphes précédents montrent que, compte tenu du nombre important des interactions potentielles et de leur conséquences, un processus, où les deux volets avion et arme se rencontrent dans des états de définition assez avancés, ne peut être que long et coûteux dans l'hypothèse où l'on cherche à minimiser les non satisfactions par rapport au besoin exprimé par l'utilisateur.

C'est malheureusement le processus actuel.

5 LES AXES D'EVOLUTION DU PROCESSUS

Le constat illustré dans le chapitre précédent conduit Dassault Aviation à préconiser une démarche commune entre l' « avionneur - architecte industriel » et le « missilier » dès les études amont d'un projet avion/arme. Dans le cadre de cette démarche, les efforts porteront sur les points suivants :

1. l'**analyse globale du besoin opérationnel** pour identifier et prédimensionner **au plus tôt** :
   - ◊ les contextes et concepts d'emploi opérationnels du couple avion/arme,
   - ◊ les termes d'échanges entre les phases vulnérables respectives de l'avion et de l'arme (pénétration avion versus portée arme par exemple).
2. l'**analyse technique globale de la mission** pour identifier **au plus tôt** les points dimensionnant et leurs conséquences sur le besoin opérationnel,
3. l'**identification des interactions majeures**,
4. la **définition du "juste" besoin avion et arme** ce qui demande :
   - ◊ une connaissance approfondie du besoin global avion/arme (aérodynamique, discrétion,...),
   - ◊ une allocation de performance entre les deux systèmes,
   - ◊ une répartition des traitements système de la conduite de tir intégrant les ressources disponibles de part et d'autre.

Le succès de cette démarche passe par :

1. un management des fonctions communes avion/arme,
2. une utilisation accrue des simulations "avion + arme" notamment à des fins de maquettage au plus tôt.

Ces deux points sont détaillés dans les paragraphes suivants.

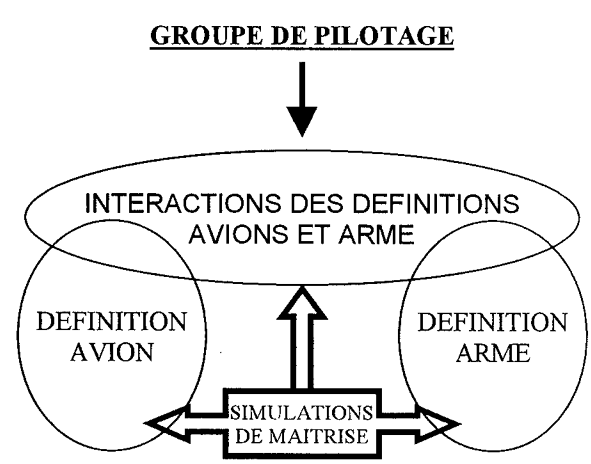
Pour la phase de développement une procédure de travail est déjà mise en place. Le gain escompté sur le déroulement de cette phase semble plus limité et passe par une démarche commune des industriels sur les phases antérieures.

5.1 Management des fonctions communes

Les projets avion et arme sont conduits dans les règles de l'art dans chaque société, par des équipes assurant toutes les tâches nécessaires au bon déroulement du projet ainsi qu'à sa cohérence. Seules, les fonctions communes relevant à la fois de l'avionneur et du missilier ne bénéficient pas de cette gestion : chaque équipe n'a pas les moyens en terme de connaissances techniques et de responsabilité de superviser de façon efficace ces fonctions qui relèvent des deux Industriels.

Aussi, Dassault Aviation préconise de créer une entité ayant pour objectif d'assurer le pilotage des fonctions communes à l'avion et à l'arme vis à vis des critères de performances techniques, coûts et délais.

Ce groupe est constitué par des représentants des deux sociétés en relation avec des correspondants des utilisateurs et de leurs représentants.



Les objectifs du groupe sont :

- identifier les interactions majeures et leurs conséquences sur les domaines connexes,
- définir précisément le besoin avion et missile pour toutes les interactions communes,
- assurer la cohérence des choix et des études,
- analyser les risques industriels,
- effectuer une analyse de la valeur.

Le groupe de pilotage s'appuie sur un document intitulé "Dossier d'interactions avion/arme" présentant chaque

fonction commune dans son environnement et le besoin et la contrainte associés. Il s'appuie également sur un outil permettant de gérer la cohérence des chaînes fonctionnelles notamment en terme d'informations échangées et de contraintes temporelles.

5.2 Utilisation accrue au plus tôt des simulations « avion +arme »

La démarche préconisée consiste à développer et à maintenir l'utilisation des simulations " avion + arme " tout au long des phases d'études amont, de faisabilité, de définition et de développement du projet.

Ces simulations pourront être constituées par **regroupement de modèles réalisés par différents Industriels** en particulier dans les cas, identifiés par le groupe de pilotage, où les interactions entre l'avion et le missile sont fortes.

Les efforts porteront sur :

- **l'utilisation des simulations au plus tôt** (analyse opérationnelle, analyse technique globale de la mission, dimensionnement, ...) **comme outils d'étude de concept(s) de système futur** ,
- **l'utilisation des simulations comme outils de qualification et de validation** des différents « sous-systèmes » et du système global,
- **la cohérence des hypothèses opérationnelles et des scénarios** utilisés dans les différentes simulations mises en œuvre **aux différents stades du processus méthodologique,**
- **la cohérence des environnements** (sur les aspects objets de la simulation et informatique) et **les capacités d'interconnexion** mono et/ou multi-sites **des différentes simulations** permettant entre autres d'intégrer ou d'interconnecter différents niveaux de modélisations voire des équipements réels tout au long du projet " avion + arme "

La démarche s'appuie également sur une **analyse "Choix / Spécifications / Planification" des simulations** à mettre en œuvre. Cette analyse est menée au début de la phase de faisabilité et se concrétise dans l'établissement et la mise à jour tout au long du projet "avion + arme" d'un document intitulé *"Dossier de définition des moyens d'étude"* qui contient:

- **les éléments de choix des simulations.** Ces éléments synthétisent pour chacune des simulations les réponses des Industriels aux questions suivantes:
  - ◊ quel est l'objectif pour la simulation? (que veut-on étudier?),
  - ◊ quelle est la phase de mise en place? (quand dans le projet ?),
  - ◊ quelle est la représentativité souhaitée pour la simulation?,
  - ◊ quelles sont les conséquences sur le projet (performances, délais, coûts) d'une non mise en place de la simulation?

  Cette étape s'appuie sur l'analyse des interactions potentielles.
- **les éléments de spécifications des simulations.** Ces éléments décrivent pour chaque simulation:
  - ◊ les objectifs techniques de la simulation: définition de la fonction à simuler, de ses interfaces avec le monde extérieur; définition des modèles à implanter;....
  - ◊ la structure informatique, le langage de programmation, le temps d'exécution, ...
  - ◊ le(s) scénario(s) d'étude.
- **le planning des simulations.** Ces éléments décrivent pour chaque simulation:
  - ◊ la place de la simulation dans la vie du projet,
  - ◊ son échéancier détaillé (début des travaux de réalisation, début des tests unitaires,..).

Trois types d'outils de simulation et de modélisation sont envisagés dans le cadre de cette démarche :

- des outils de maîtrise du fonctionnel pour réaliser les études technico-opérationnelles et de conduite de tir (concept, IHS...),
- des outils de maîtrise des interactions physiques (compatibilité, masques, système électrique...),
- des outils de maîtrise des performances permettant d'aboutir à l'engagement commun des Industriels.

5.2.1 Les outils de maîtrise du fonctionnel

- <u>**Les simulations technico-opérationnelles**</u>

  Les simulations technico-opérationnelles prennent fondamentalement en compte le fait que le système « avion + arme » à étudier est en interactions potentielles ou effectives avec un environnement et que sa mission (dans ses objectifs et son déroulement) n'est pas intrinsèque mais dépendante de « facteurs extérieurs ».

  Une telle approche, dans la conception d'un systèmes d'arme, peut être synthétisée par la terminologie « attaque/défense » où l'attaque désigne de façon très globale le système en étude et son environnement ami et la défense l'environnement hostile avec lequel il sera en interaction conditionnant sa vulnérabilité et donc en partie la réussite de la mission.

  Les exploitations de ces simulations ont pour objectif global de fournir à l'utilisateur des éléments lui permettant de préciser son expression de besoin et de quantifier ses concept d'emploi :

  ◊ **Préalablement à la phase d'étude de faisabilité**, ces études sont destinées à proposer au futur utilisateur des éléments

permettant d'initialiser son expression de besoin. Ces éléments sont obtenus au travers de l'identification des grands termes d'échanges entre l'avion et l'arme notamment en terme de compromis « coût / efficacité » vis-à-vis du coût global de la mission.

◊ **En phase d'étude de faisabilité,** ces simulations permettent de donner rapidement une représentation globale du besoin et une vision avancée du système en situation dynamique dans un environnement (notion de prémodèle de système candidat).aidant ainsi à spécifier plus finement le besoin du couple « avion + arme »:
   - en surveillant les grands termes d'échanges identifiés précédemment,
   - en identifiant les conséquences sur la mission de différentes solutions pouvant être issues d'études techniques menées en parallèle sur des points dimensionnants des définition avion et arme (alignement par exemple). Ce rebouclage se poursuit lors des phases de définition et de développement du produit.

◊ **En phase d'étude de définition,** ces simulations permettent de suivre l'évolution des différents critères technico-opérationnels retenus lors de la phase de faisabilité en fonction de l'avancement de la définition du couple « avion + arme » autorisant ainsi le rebouclage permanent entre les volets technique et opérationnel.

◊ **En phase d'étude de développement,** ces simulations peuvent être utilisées d'une part pour préciser des techniques d'emploi du couple « avion + arme » face à certaines situations opérationnelles et d'autre part dans le cadre d'une démarche d'engagement de performances si certains critères définis lors de la phase de faisabilité en faisaient l'objet

- **<u>Les simulations de conduite de tir</u>**

Les simulations d'études de conduite de tir ont pour objectif d'étudier les interactions entre le système « avion + arme » et l'équipage tout au long de la mission en intégrant un environnement permettant de générer des événements pouvant perturber ces interactions. Ces simulations sont du type "Homme dans la boucle". Elles sont temps réel ou pseudo temps réel

Deux types de simulations d'études de conduite de tir sont employées:

◊ Celles utilisées pour réaliser des **maquettages rapides** de tout ou partie de la conduite de tir; ces simulations sont utilisées plus particulièrement pour présenter les résultats d'études techniques ayant une répercussions sur la présentations d'informations à l'équipage (exemple: robustesse du calcul d'une autorisation de tir au vol en suivi de terrain de l'avion ,....). Ces simulations ne nécessitent pas la mise en œuvre d'un environnement des postes d'équipage totalement représentatif.

◊ Celles utilisées pour **étudier et /ou évaluer les principes de mise en œuvre de la conduite de tir** au cours d'une mission. Ces simulations nécessitent la mise en œuvre d'un environnement des postes d'équipage totalement représentatif.

En phase d'étude de faisabilité, l'objectif recherché est. d'établir et d'illustrer les principes d'emploi de la conduite de tir s'intégrant dans le concept d'emploi général du système tout en s'assurant de la faisabilité en terme de dimensionnement système de cette conduite de tir. Cet objectif est atteint au travers d'une simulation de la vision à terminaison de la conduite de tir. Cette simulation réalisée dans un environnement des postes d'équipage totalement représentatif de l'état de définition en cours s'appuie sur des simulations de maquettage rapide des résultats d'études techniques

En phase d'étude de définition, l'objectif recherché est d'illustrer les Spécifications Globales de la conduite de tir tout en surveillant la faisabilité de celles-ci en terme de respect des allocations système. Cette simulation, est dérivée de celle établissant la vision à terminaison de la conduite de tir. Comme cette dernière, elle est réalisée dans un environnement des postes d'équipage totalement représentatif de l'état de définition en cours et peut s'appuyer sur des simulations de maquettage rapide des résultats d'études techniques.

En phases d'étude de développement, de production et d'utilisation, l'objectif recherché est d'assurer l'entraînement des équipages. (à des fins de préparation d'essais ou à des fins de préparation des missions à réaliser) par l'utilisation d'une simulation réalisée dans un environnement des postes d'équipage totalement représentatif de l'état de définition en cours. Cette simulation est construite en intégrant la simulation de fin de phase de définition dans un environnement tactique plus complexe et/ou en intégrant à celle-ci des logiciels d'équipements réels

5.2.2 Les outils de maîtrise des interactions

Les simulations techniques ont pour objectifs d'établir, valider et qualifier les définitions de l'avion et de l'arme au travers de l'étude et de l'analyse des interactions techniques entre ceux-ci. En phase de conception, ces simulations sont utilisées comme une aide à la spécification; en phases de développement et de production, elles sont utilisées comme une aide à la

validation. Dans ces simulations, l'homme n'est pas dans la boucle.

A titre d'exemple, les aspects alignement et désignation d'objectif sont deux interactions majeures qui nécessitent des simulations techniques afin, entre autres, de définir une méthode d'alignement assurant le besoin de l'arme (précision, durée de validité de l'alignement, ...) tout en minimisant les contraintes sur le porteur (manœuvre d'alignement, ...) et d'établir le meilleur compromis " performances de désignation de l'objectif / performances de navigation de l'arme / caractéristiques de l'autodirecteur"

Dans le futur, l'évolution de la technologie informatique autorisera des simulations multidomaines qui permettront une approche encore plus complète de la réalité physique. Par exemple, les effets vibratoires et thermiques pourront être combinés au cours d'une même simulation. Ces simulations permettront ainsi de déceler certains problèmes qui actuellement ne seraient vus qu'au cours des essais avec équipements réels.

En phase d'étude de faisabilité, l'objectif recherché est d'analyser les différentes solutions possibles notamment en terme de dimensionnement système de la Conduite De Tir de performances et de soulever les points durs vis à vis des critères de besoin global qui peuvent résulter des simulations technico-opérationnelles. A ce stade du projet, ces simulations sont donc réalisées pour vérifier les ordres de grandeurs des principales chaînes fonctionnelles.

En phase d'étude de définition, l'objectif recherché est d'aboutir à une spécification des fonctions communes optimale vis à vis des performances, du dimensionnement système, et de la robustesse au concept d'emploi. Les simulations utilisées sont établies à partir de celles de la phase de faisabilité en augmentant la finesse de la modélisation et de l'environnement. Ces simulations permettent pour les solutions retenues à l'issue de la phase de faisabilité l'étude des modes dégradés de celles-ci. Ces simulations sont également utilisées en fin de phase de définition pour l'estimation des performances du système "avion + arme" dans des situations et des environnements représentatifs et dimensionnants.

En phases de développement et de production, les simulations d'études sont mises à jour en fonction des évolutions de la définition. Des simulations fines des équipements sont réalisées. Un outil de simulation représentatif de la définition matériel et/ou logicielle sera disponible. Les simulations sont utilisées à des fins:

◊ de validation de la définition matérielle et logicielle de la fonction,
◊ de validation des premiers prototypes au travers des simulations hybrides,
◊ de choix des scénario d'essais.

La mise en place de ces moyens de validation a pour but de déceler les éventuelles erreurs dans les phases amont à la réalisation et de limiter les aléas au cours de l'intégration.

5.2.3 Les outils de maîtrise des performances

Les outils de maîtrise des performances ont deux objectifs :

◊ permettre à l'avionneur et au missilier de quantifier les performances globales du système « avion + arme »

◊ permettre à l'avionneur et au missilier d'établir et de démontrer (si la simulation fait partie des moyens de démonstration agréés par l'utilisateur) des valeurs d'engagement de performances

Compte-tenu de cette démarche continue et de façon identique aux outils décrits dans les chapitres précédents, les outils de maîtrise des performances évoluent tout au long du développement du projet « avion + arme »

De façon générale, les outils de maîtrise des performances sont relatifs à une chaîne fonctionnelle globale. Ainsi dans le cas de notre exemple d'armement à imagerie, la chaîne de précision d'impact inclut aussi bien les aspects désignation par un capteur de bord de l'avion, que les aspects localisation avion ou encore les aspects alignement de la centrale missile, localisation et navigation (y compris dans la phase terminale) du missile.

Ces outils sont élaborés à partir de ceux mis en œuvre dans le cadre de la maîtrise des interactions mais peuvent aussi inclurent des modélisations non directement de responsabilité de l'avionneur et/ou du missilier comme celles des capteurs de désignation dans notre exemple.

6 CONCLUSIONS

Les propositions de Dassault Aviation ont pour objectif de constituer un processus de développement d'un programme avion/arme commun à un avionneur et à un missilier répondant aux deux objectifs suivants:

- améliorer les performances globales du système "avion + arme",
- diminuer les cycles et les coûts des travaux d'études et de développement du système "avion + arme"

Pour cela il est très important :

- d'identifier dès que possible les points dimensionnants de la mission et de rechercher le juste besoin "avion + arme". Il est par ailleurs souhaitable que les industriels participent largement à l'établissement des spécifications de besoins,
- de s'appuyer le plus possible et au plus tôt sur la simulation pour gagner en temps de développement,
- d'identifier dès que possible les interactions (et non plus simplement des interfaces) avion /

missile, d'une part, mais aussi entre systèmes (avionique / aeromécanique par exemple) d'autre part,

- de procéder à des analyses de la valeur en définition et en développement.

Ce qui nécessite :

- de mettre en place un « groupe de pilotage » constitué de représentants des sociétés en relation avec les Services de l'Etat. Ce groupe assure l'identification et le suivi des interactions (à l'aide d'un document « d'analyse des interactions » et du « dossier d'interactions avion/arme ») et assure la cohérence des choix. Il pilote, par ailleurs, l'analyse de la valeur et des risques industriels,
- d'établir dès la phase de faisabilité un document de « définition des moyens d'étude » qui définit les simulations à mettre en oeuvre (ainsi que le calendrier associé). Ce document est entretenu tout au long du projet,
- dans les cas, identifiés par le groupe de pilotage commun missilier / avionneur, où les interactions entre l'avion et le missile sont fortes de regrouper les modèles des éléments intervenant dans la chaîne globale.

ACTIVE CONTROL OF WEAPON BAY ACOUSTICS

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ABSTRACT

To increase the range and payload of both existing and future aircraft, while maintaining or increasing mission survivability, weapons must be carried in low drag/low observable configurations. Existing external weapons carriage technology accounts for as much as 30% of total vehicle drag and prohibitive increases in radar signature. Internal weapons carriage solves signature issues, but substantially increases aircraft size while limiting weapon payloads to the size of weapon bays. New innovate and novel ways of both internal and external weapons carriage will be crucial to fighters of the next century. However, the new internal bays create a challenge to develop methods to suppress and control the internal flow induced acoustic environment in the weapons bay.The objective of the current wind tunnel test program was to define the baseline acoustic environment in a cavity and evaluate the effectiveness of active suppression concepts. The concepts consisted of leading edge oscillating flaps and leading edge pulsed fluidic actuation. Both concepts were evaluated for a range of parameters and the results indicate that either will successfully control the instabilities in the shear layer and thus suppress the flow induced acoustic environment in the cavity. The pulsed fluidic actuator was found to be more robust.

INTRODUCTION

The flow induced cavity acoustic phenomenon consists of an unstable free shear layer impinging on the down stream wall of the cavity. The impingement point becomes the source of acoustic energy which then propagates to the front wall of the cavity and interacts with the free shear layer at the point of separation where it is most receptive to energy. If the frequency and phase of the acoustic energy coincides with the instabilities of the shear layer, resonance can occur. That is, the energy entering the shear layer at the leading edge is amplified as it is transported down stream to the trailing edge where it interacts with the wall completing the feedback loop. If the free shear layer is forced at some frequency other than the acoustic feedback frequency so that enough energy is extracted from the shear layer, the acoustic feedback energy will not be amplified and the acoustic environment in the cavity will be controlled.

One of the earliest indications that the feedback loop could be interrupted by altering the feedback frequency of the shear layer was published by Shaw et al (1) showing that if the fore-aft position of the leading-edge passive suppressor was varied, the magnitude of suppression of the acoustic tones in the cavity was also varied. The position of the leading edge suppressor controls the time of travel of a disturbance from the suppressor to the down stream wall of the cavity, hence the frequency, while the cavity feedback frequency remains fixed. For maximum amplification the two frequencies must coincide. Thus it was shown that if the shear layer frequency is altered, the feedback loop is opened.

Another study by Gharib (2) clearly demonstrated that cavity induced oscillations could be controlled by excitation of the shear layer over the cavity. He sinusoidally introduced thermal energy ahead of the cavity to excite the Tollmien-Schlichting waves in the attached boundary layer so that they would be amplified by the boundary layer before it separates at the leading edge of the cavity. His results showed that he could either attenuate or amplify the cavity resonate tones by selecting the proper forcing frequency of the shear layer. Oster and Wygnanski (3) used an oscillating flap as their method to introduce time dependent energy into the flow. Their results showed that the free shear layer may be controlled at frequencies an order of magnitude lower than the initial instabilities of the shear layer. This is very encouraging for full scale applications because it may only require a very low frequency source of energy to control the acoustic environment in an aircraft weapons bay.

The use of a low excitation frequency to control the shear layer over a cavity was demonstrated by Sarno and Franke (4). They used a leading edge oscillating 90 degree spoiler and pulsed air injection with excitation frequencies of 220 Hz and 80 Hz respectively. The acoustic resonant frequency of the cavity was of the order of several

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

kilohertz but the excitation frequency was less than 220 Hz. The results were promising since they achieved up to 20 dB suppression.

Shaw and McGrath (5,6) applied active flow Drawing control to the weapons bay acoustic suppression problem by wind tunnel testing a shallow cavity model with a leading edge oscillating flap as the flow actuator. Results were obtained for Mach numbers from 0.6 to 1.89 for flap frequencies up to 35 Hz. The cavity resonance was above 1500 Hz for all Mach numbers while the excitation frequency was almost two orders of magnitude lower. Suppression of the cavity tones was achieved at all Mach numbers. The magnitude of the suppression was between 6 and 15 dB. They desired to evaluate the effectiveness of exciting the free shear layer at some frequency above the cavity resonance and the method selected was to place a small wire (referred to as a high frequency tone generator-HFTG) in the boundary layer just ahead of the cavity leading edge. They sized the wire to have a shedding frequency in the range of 25 kHz, well above the cavity resonance. The HFTG resulted in complete suppression of the resonant tones as well as 5-10 dB reduction in the broadband levels. Thus they have shown that the flow induced cavity acoustic levels can be controlled by excitation of the shear layer at either low or high frequencies.

The above results inspired the current test of active control of weapons bay acoustics on a scale model aircraft. The flow actuators selected were a leading edge flap and pulsed fluidic source. The test was conducted in the Calspan 8-foot transonic wind tunnel located in Buffalo, New York. The facility can operate at pressures from 0.25 to 3.25 atmospheres, velocities from 0 to Mach 1.3, and Reynolds number up to 5 million/foot.

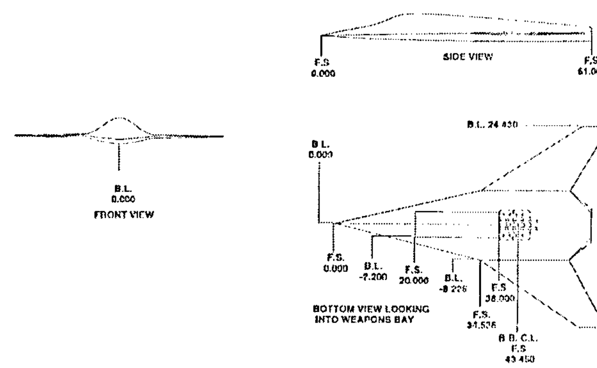

Figure 1. Drawing of parent model

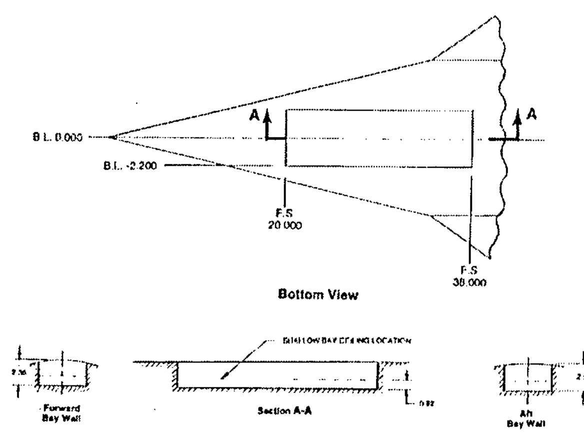

Figure 2. Drawing of weapons bay dimensions

DESCRIPTION OF TEST

Model Description

Figure 1 shows the overall dimension of the parent model while the dimensions of the weapons bay are shown in Figure 2. The bay had a moveable ceiling allowing for L/D ratios of 13.49 and 8.25. The parent model was a blended wing low observable design which has been tested with numerous external store configuration as well as internal configurations. Bay doors were tested to determine the effect they had on the acoustic levels as well as the loads on the doors.

Active Acoustic Suppressors

The active flow control actuators were a leading edge flap, pulsed fluidic actuator, and a high frequency tone generator. A drawing of the flaps is given in Figure 3 which shows the two designs, straight and notched. Figure 4 shows how the flaps were installed on the model. The pulsed fluidic actuator is shown in Figure 5. The three high frequency tone generators consisted of cylindrical

rods of different diameters installed at the leading edge of the cavity.

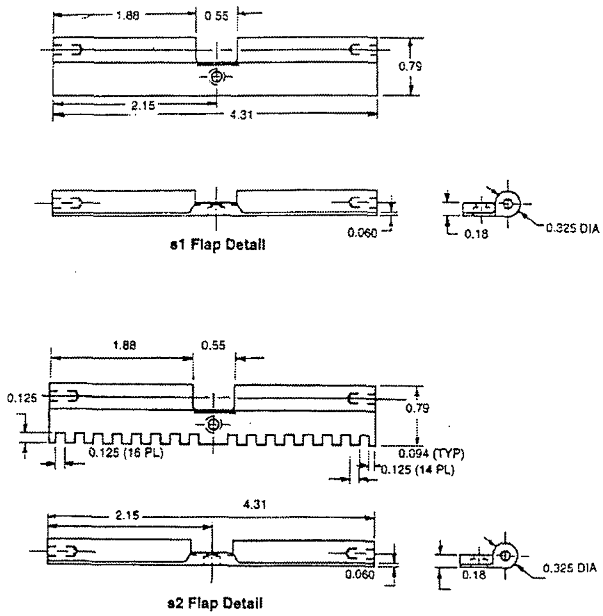

Figure 3. Flap Configurations

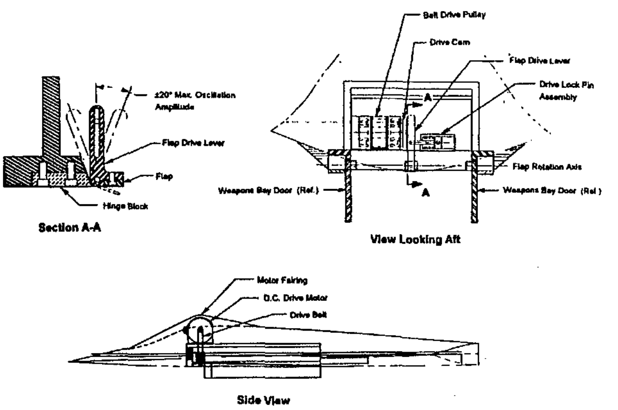

Figure 4. Oscillating Flap System Installation

Instrumentation and Data Acquisition

The weapons bay was instrumented with 6 Endevco 15 psi dynamic pressure transducers as shown in Figure 6. The output from the transducers was recorded on a Metrum recorder. The data were digitized at 8 samples per cycle with a bandwidth of 2,500 Hertz for the long bay and 5,000 Hertz for short bay.

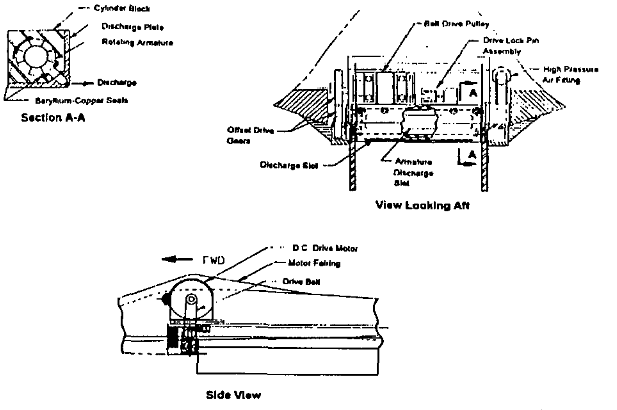

Figure 5. Pulsed Air Jet System Installation

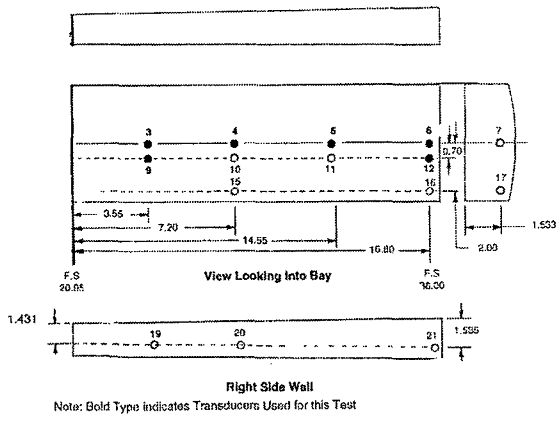

Figure 6. Dynamic Pressure Transducer Locations

Test Facility and Procedures

Testing was conducted in the Calspan 8-Foot Transonic Wind Tunnel. This tunnel is a closed-circuit, single return pressure tunnel capable of providing test section Mach numbers ranging from

0.0 to 1.3, at stagnation pressures ranging from 0.25 to 3.5 atmospheres. The test section Reynolds number may be varied from 0 to 12.5 million per foot. The test section is 8-by-8-by-11 feet and is equipped with perforated walls to reduce transonic blockage effects. Figure 7 shows how the model was installed on the sting in the wind tunnel test section and all electrical connections were made. An end-to-end calibration was completed on most of the dynamic pressure transducers. Some of them were inaccessible because of the size of the calibrator. Before each data record was made tunnel conditions were stabilized and a thirty second record was made. Data were obtained for four Mach numbers, four flap frequencies, and typically five mass flow rates.

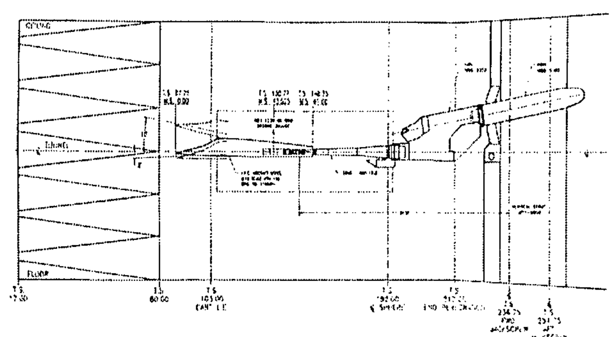

Figure 7. Drawing of Model Installed In The Test Section

DISCUSSION OF DATA

Baseline Data

Only data from microphone 6 will be presented for the evaluation of the effectiveness of the active suppression concepts. Microphone 6 is located on the floor(or roof) of the cavity at the rear. Figure 8 shows the spectrum for a Mach number of 0.85. For Mach number 0.6 modes 2 and 3 are nearly the same level but at Mach 0.85 mode 2 is by far the highest level at 162 dB. The same amplitude distribution was observed for Mach 0.95 and 1.05. The amplitude of mode 2 for Mach 1.05 is 166 dB.

High Frequency Tone Generators

Three different diameter (1/16, 1/8, 3/16, inches) tone generators were tested for their ability to control the acoustic levels in the cavity. The centerline of each of the generators was located at a height of 0.300 inches. Figure 9 shows typical spectra for the largest diameter tested. In general

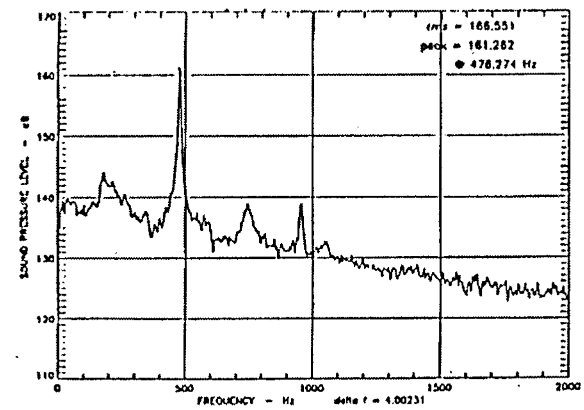

Figure 8. Baseline Spectrum for Mach Number 0.85

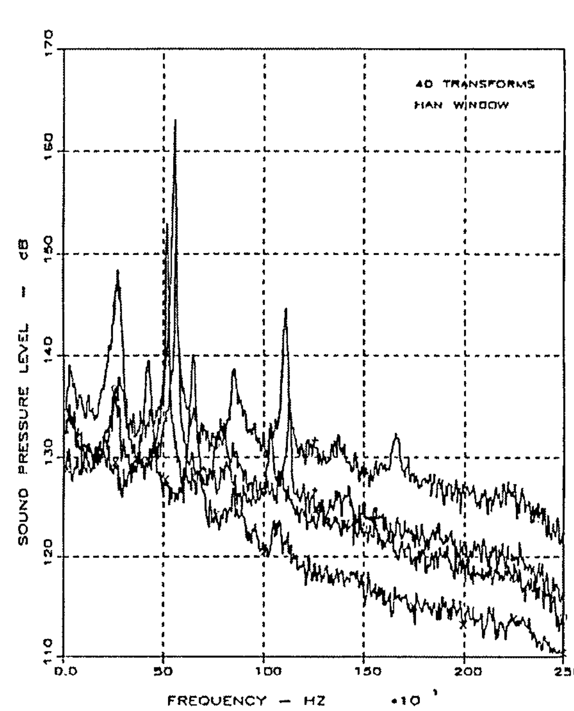

Figure 9. Spectra for the 0.187 Diameter High Frequency Tone Generator for Each Mach Number x=0.60; o=0.85; *=0.95; +=1.05

the tones are still prominent but some attenuation was achieved as As shown in Figure 10. The data clearly show that for both subsonic and supersonic speeds the larger the diameter the more suppression is realized. The generators were most

effective at the subsonic speeds. There is some question as to what the real impact the generators

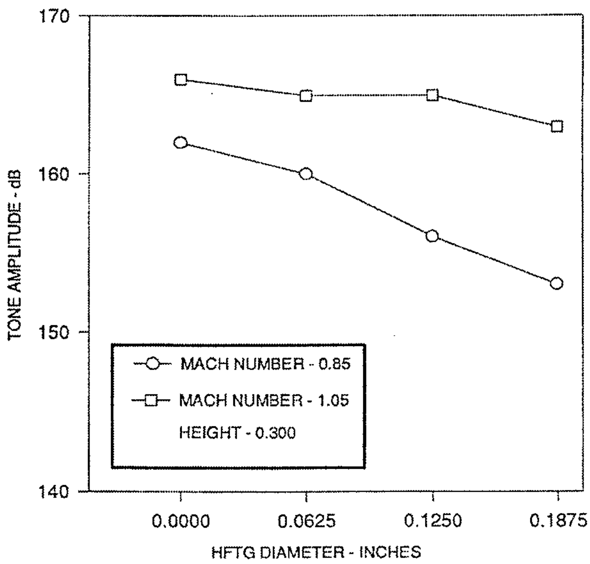

Figure 10. Tone Amplitudes for All Three High Frequency Tone Generators

are having on the shear layer. One explanation is that the generators are seeding the shear layer with high frequency small scale vortices which are then amplified as they are transported downstream by extracting energy from the larger scale instabilities in the shear layer thus preventing the acoustic feedback tone from being amplified in the shear layer. Another explanation is that the generators are simply thickening the boundary layer as it separates changing the instability growth rates in the free shear layer which results in the acoustic feedback tone not being amplified. Since the smallest diameter generator(0.0625 inch) was less then 20 percent of the total boundary layer, and some suppression was realized, it is believed that the first explanation is most valid. However, the tone generator used in the test conducted by McGrath and Shaw (Ref 19) was of the order 50 percent of the boundary layer thickness and the feedback tones were completely suppressed and the broadband levels were also greatly reduced. These results seem to substantiate the second explanation. Additional tests with flow visualization and shear layer diagnostics are needed to determine the exact affect the generators are having on the shear layer.

Flaps

Straight and notched flaps(Fig. 3) were tested for their effectiveness in suppressing the acoustic tones in the cavity. The flaps were oscillated from 2 degrees about a neutral angle of 0 degrees to 20 degrees about a neutral angle of 20 degrees for frequencies from 5 Hertz to 100 Hertz. Figure 11 shows a typical spectrum for the maximum excitation condition for a Mach number of 0.85 and frequency of 5 Hertz. If all

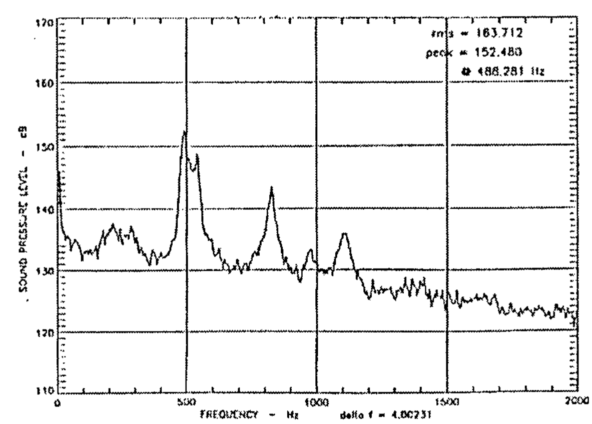

Figure 11. Spectrum for Flap Maximum Deflection: Mach-0.85; Excitation Frequency-5 Hertz

of the levels are compared to the baseline levels the results show that the 2 degree excitation case affords very little or no suppression while the 20 degree case results in 10 dB suppression of the maximum tone and 3-4 dB suppression of the broadband levels. Intermediate flap angle results are summarized in Figures 12 and 13. The data clearly show that for low angles of excitation (deflection) very little suppression is achieved, but as the excitation is increased the amount of suppression is also increased. The maximum suppression occurs at the maximum excitation for all cases. For the 20 degree neutral position and 20 degree excitation the displacement height of the flap is approximently the height of the boundary layer. This configuration is feasible for a small scale test but is not considered feasible for full scale application on an aircraft.

The frequency of the flap actuator was varied from 5 to 100 Hertz. The effect of exciation frequency is displayed in Figure 14. The results indicate that the 5 Hertz excitation resulted in the

most suppression of the tone amplitude but it appears that at some frequency above the 100 Hertz maximum test frequency that a higher level of suppression could be realized. This is easily explained

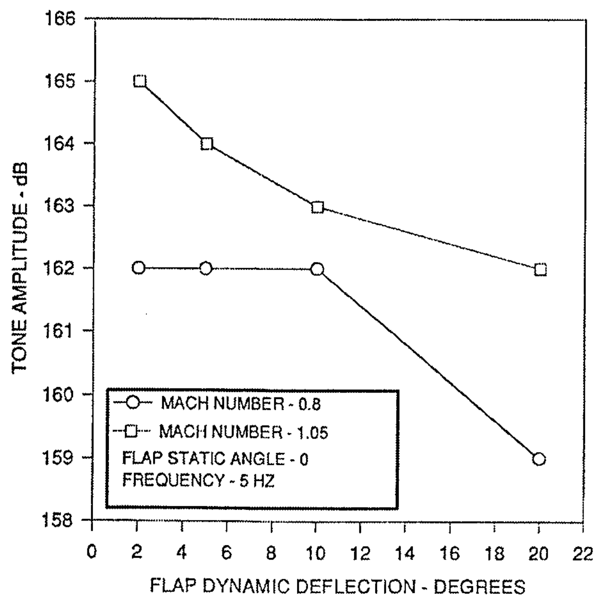

Figure 12. Amplitudes for Flap Static Angle of 0 Degrees

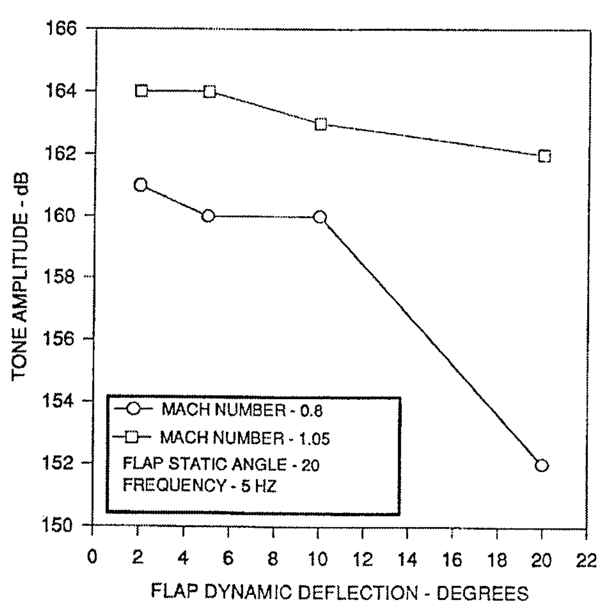

Figure 13. Amplitudes for Flap Static Angle of 20 Degrees

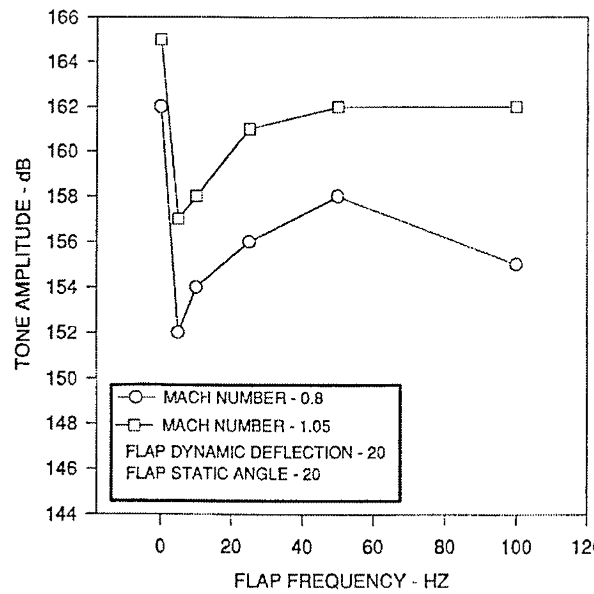

Figure 14. Amplitudes for Various Flap Excitation Frequencies

by the fact that the instability growth rates in the free shear layer is frequency dependent. It is desirable to operate the flap actuators at a higher frequency but it is not physically feasible because of the dynamic constraints of the system.

Pulsed Fluidic Actuator

Pulsed fluidic injection at the leading edge of the cavity was used as an actuator to impart time dependent energy into the shear layer to control the acoustic environment. The actuator is shown in Figure 5. The jet was rectangular with dimensions of 0.035 or 0.10 by 3.75 inches and located as close to the leading edge of the cavity

Additional suppression over steady mass addition is achieved when the mass flow is pulsed. For 0.01 lbm/sec mass flow the amount of addition suppression is limited except at a pulsing frequency of 100 Hertz where 7 dB was achieved. However, at the higher mass flow rates of 0.05 and 0.10 very significant suppression was achieved even at the lower frequencies. Comparing the spectra for the same mass flow rates reveal that more than 20 dB addition suppression can be realized by increasing the mass flow from 0.01 to 0.10 for the same pulsing frequency. Thus, the magnitude of suppression is a strong function of the mass flow rate and the pulsing

frequency. It is worthy note that Kimura et. al.(Ref. 7) concluded that active control in a boundary layer was related to the product of the actuator's peak amplitude and the excitation(pulsing) frequency of the actuator. In their case the actuator was a pulsed flap and in the current case the actuator is a pulsed air jet. It appears that mass flow requirements can be controlled by varying the excitation frequency. This would help to decrease the amplitude of the tones in the spectra generated by the pulsed mass addition. Figure 15 shows a spectrum for pulsing at 25 hertz with a mass flow of 0.1 lbm/sec and Mach number of 0.85. The tone was suppressed 20 dB.

The major trends in the data are summarized in Figures 16-20. The acoustic levels generated in the cavity due to steady state mass addition for the three injection angles tested are shown in Figure 16. These levels are for no tunnel flow and for the rear of the cavity. When the jet is at zero degrees(parallel to the flow) the level is over 160 dB but diminishes to less than 130 dB when the jet is at 90 degrees. The jet was found to be more effective at 90 degrees and one might be led to think that the results in Figure 16

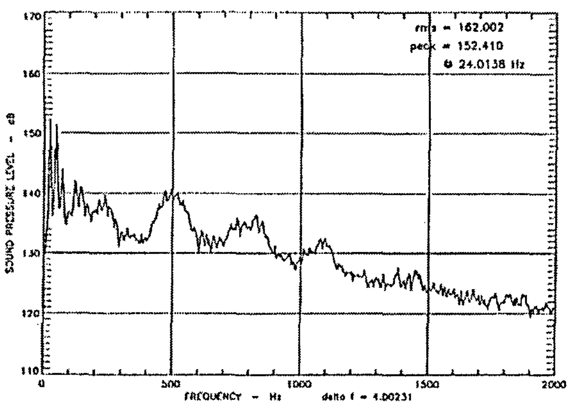

Figure 15. Spectrum for Pulsing at 25 Hertz, 0.1 lbm/sec mass flow, Mach 0.85

would explain the more effectiveness. However, a better explanation is that there is a greater momentum transfer into the shear layer when the jet is oriented at 90 degrees. The effect of mass flow rate is illustrated in Figure 17 for the three injection angles with no tunnel flow. As predicted the amplitude increases with mass flow for all three angles. The effect of mass flow on the tone

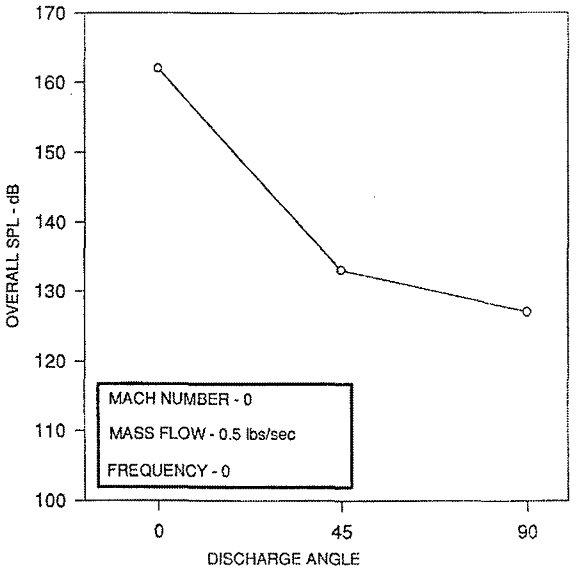

Figure 16. Effect of Discharge Angle on the Overall Level

amplitude with tunnel flow is presented in Figure 18 for an injection angle of zero degrees. Again the amplitude is attenuated with increasing mass flow. For the 1.05 Mach Number case the tone was

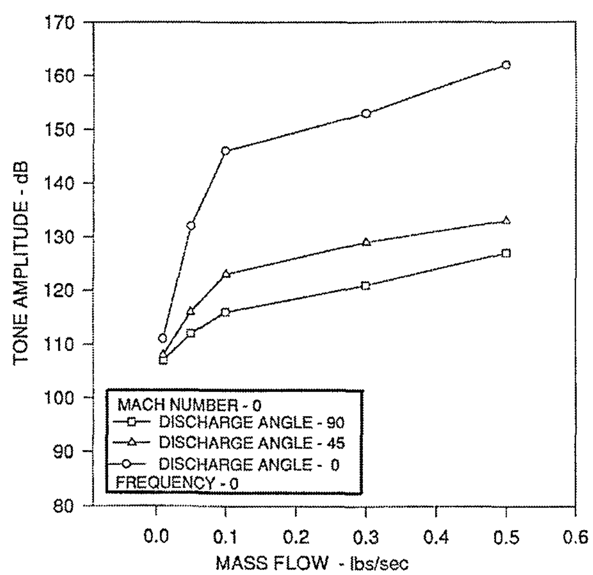

Figure 17. Effect of Mass Flow on the Tone Level With Wind Tunnel Off

suppressed 15 dB. The effect of pulse frequency is presented in Figure 19 for zero degree discharge and a mass flow rate of 0.10. It is seen that an additional 10-15 dB suppression can be gained by pulsing the mass flow. It appears that the amplitude monotonically decreases with increasing pulse frequency. For this case pulsing is more effective for the subsonic regime. As stated earlier the 90 degree injection angle was the most effective, this can be observed in Figure 20 for the 0.1 mass flow condition. Comparing Figures 19 and 20 it is seen that the 90 degree case results in a tone level more than 10 dB lower that the zero degree case. A higher momentum

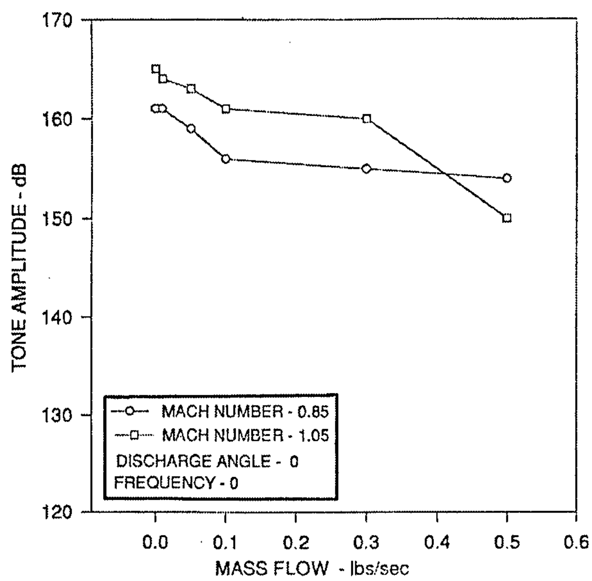

Figure 18. Effect of Mass Flow Rate on the Tone Level With Wind Tunnel On

transfer is realized for the 90 degree configuration, thus resulting in a greater level of control of the instabilities in the shear layer and ultimately the flow induced acoustic levels in the cavity.

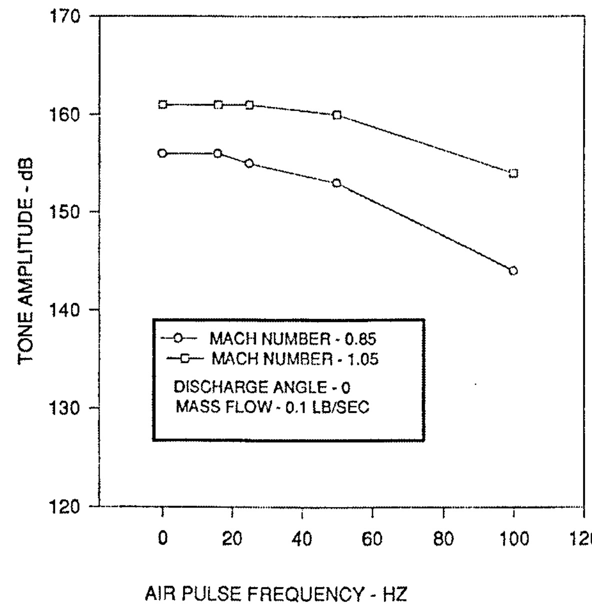

Figure 19. Effect of Pulse Excitation Frequency on the Tone Level for 0 Degree Discharge Angle

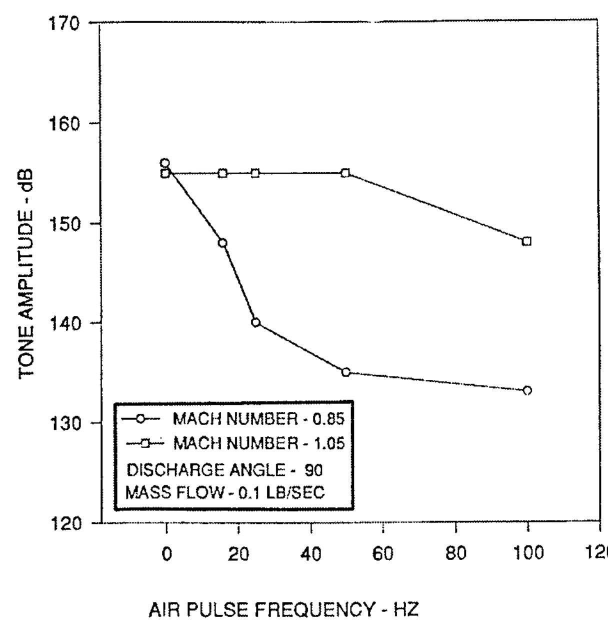

Figure 20. Effect of Pulse Excitation Frequency on the Tone Level for 90 Degree Discharge Angle

SUMMARY AND CONCLUSIONS

A wind tunnel test was conducted on a blended wing aircraft model with a weapons bay to evaluate the effectiveness of several active acoustic suppression concepts. These consisted of leading edge oscillating flaps, pulsed fluidic jets. and a high frequency tone generator. The suppression provided by the various devices was quite varied. For specific tones and Mach numbers as much as 30 dB could be achieved. All three devices tested were effective for some condition. For the high frequency tone generator it was found that the larger

the diameter the more suppression results. For the oscillating flap it was observed that effective suppression can be realized only with large deflection angles(near 20 degrees) and the most effective excitation frequency was the lowest one tested of 5 Hertz. The acoustic feedback phenomenon and shear layer receptivity are very sensitive to the state of the boundary layer at the point of separation. Thus, selection of the most effective active suppression concept should be based on a configuration as close to the full scale one as possible and then effective suppression will require a robust controller to insure that control of the actuators are being optimized for the current configuration and flow conditions.

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Structural Deformation – A New Challenge to the Accuracy of Separation Codes

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Summary

In general, the state of the art analysis of the separation behaviour of an external store doesn't consider the effects of local structural deformations of the carriage devices and launch equipment.

Such deformations may be caused by steady/unsteady inertia and aerodynamic loads. The order of magnitude of such deformations ranges between tenths of degrees up to values of several units. If neglected within the prediction of separation behaviour, a consecutive flight test result normally comes up with a bad evidence.
The intention of this paper is to demonstrate such adverse effects which are typical for fighter aircraft carrying external stores. A way ahead will indicate how to overcome these problems by implementing more accurately measured initial conditions into the postflight separation analysis.

Thereby store trajectories computed with conventionally gathered initial conditions will be shown in comparison with conditions derived from in-flight deformation measurements in order to underline the relevance of such corrections with respect to separation autopilot design and with respect to the clearance work.

1. Introduction

In the past ten years methodologies for store separation analysis have gained a high level of efficiency and confidence. Also the capability of treating nontrivial cases within a reasonable complexity has increased considerably.

There are still several areas where further improvements are necessary and achievable. Time accurate representations of the 6 degree of freedom motions simultaneously and reciprocally interacting with the complex flow architecture around a separating store and the releasing aircraft is one of the areas which remains mostly driven by the availability of computing resources and appropriate tools. Viscous flow effects as well as the global representation of flows with multiple phases also belong to the long term goals of future efforts.

Structural interactions between store and aircraft are very well handled as far as flutter, vibration and acoustics are concerned, but still remain a progressive area for future engineering tasks concerning store separation.
The scope of this paper is to review past experiences gained with cases of store separation which were strongly affected by structural deformation implemented by the carriage components. Thereby the main objective is to provide examples how to identify structurally sensitive cases, and to show up possibilities for determining the magnitude of structural deformation effects, either by appropriate tests or by postflight analysis.

2. Characterisation

Deformation, in this context, shall be understood as a quasi steady state continuous response of the aircraft structure and the carriage equipment which are reacting to the forces and moments implemented by the inertia loads of the store in connection with the manoeuvre loads of the aircraft in addition to the resulting interference aerodynamic loads acting on the store.

Due to its aperiodic character, it can be clearly distinguished from purely harmonical and unsteady effects such as vibration and flutter, which will not be adressed to in this context.

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

Heavy stores are mostly exposed to such effects, as well as stores with distinct aerodynamic characteristics. Light weight stores with slender bodies are not potential candidates but can be involved by second line effects.

Asymmetric installation positions, off the plane of symmetry of the aircraft, are mostly exposed to such effects. Wing stations are adequately affected.

Thereby structural deformation is primarily induced by the lateral forces and moments acting on the store attachment points. The contribution of axial force, lift and pitching moment can be considered as negligibly small.

If not taken into account when analytically predicting a separation process, the presence of structural deformation may considerably deteriorate the results expected from a comparative flight test case. Fig.1 illustrates such a situation, in which the rigidly computed trajectory clearly differs from the trajectory data gained from the analysis of the flight test results.

Taking into account the rigid installation position, the predicted store motion behaves quite neutral in roll after release, whereas a strong rolling motion with rates up to 150 °/s is indicated by the flight test data.
By introducing a small installed misalignment of less than 1° in roll and yaw, the computed results can be considerably improved such as to provide a perfect agreement with the data derived from flight test. As it will be shown in the following, this alignment error was in full agreement with in-flight deformation measurements which have been carried out in parallel to this jettison test.
The good agreement is documented by the comparisons shown in fig.2 ,3 and 4 which represent the three Euler angles taken from the experiment and the two computations with and without consideration of the contributions from structural deformation.

3. Verification and Quantification by Testing

In general, Wind Tunnel measurements are considered as a standard prerequisite for external store integration programmes. At project start the appropriate key configurations have to be checked by wind tunnel testing with respect to stability, control and also carriage loads. Such an arrangement is shown in fig.5 in which most of the stores are equipped with own balances. In addition to the main balance for the aircraft loads each store balance provides a record of installed loads which are also used as initial condition for the safe separation analysis.

These loads represent the rigid aircraft properties and do not include effects implemented by structural deformation arising from aeroelasticity or manoeuvring loads.
During the flight test data acquisition phase such effects can be assessed if the store attachment and carriage devices are properly instrumented and balanced. Typical results deduced from such measurements are shown in fig.6 in comparison with the rigid data taken from the wind tunnel tests. The flight tested sideforce coefficients shown here have been assessed from records taken during wind-up turns for $\alpha > 8°$ and roller-coaster manoeuvres for $\alpha < 10°$ at minimised sideslip angles. The difference between flight test and wind tunnel coefficients is a clear indication for the presence of a steady state structural deformation as described in the preceding chapter. It varies for each flight test condition and also strongly responds to the load factor levels. The characteristic is strongly non-linear with respect to the effective angle of attack. It is also remarkable that at $\alpha > 8°$ the sideforce gradient is inverted against the trend measured in the wind tunnel.

As far as safe separation is concerned, it is not sufficient only to implement some correction loads to the installed loads in order to get the full story. In addition to this it is also necessary to specify the incremental alignment induced by the deformation, in order to provide the full description of the initial condition into the separation code.
Any angular term in roll or yaw will contribute additional terms to the release disturbance and thus change the motion of the store after release.

Bearing in mind that such deformations are quite inaccessible to theoretical analysis, the determination of these misalignments remains a main objective of further experimental efforts. A pragmatic approach to this purpose consists in using a ground-stiffness test involving a store installed to the aircraft. The general test arrangement therefore is shown in fig.7, where one can see how the hydraulic actuator is operated in order to generate predefined loads on the store installed to the aircraft. Two actuators are used one at each end of the store such as to generate symmetric and antimetric forces and moments. Fig.8 shows the sensors installed to the different areas in which the deformations had to be recorded. Typical results are shown in fig.9 and 10 , where the measured deformations are plotted against the applied total yawing moment. These functions are assessed at the nose and for the rear part of the store and have a non-linear character due to the backlash of the attachment mechanism. If these

functions are correlated to the total yawing moments computed under flight conditions, installation corrections can be deduced for each axis of the store mounted to the aircraft. Fig.11 shows such a chart giving the heading corrections derived for the store shown before in dependency of the Mach number at a loadfactor close to unity.

Now each trajectory can be computed taking into account the structural deformation. With such an input and with the knowledge of the incremental loads arising from the structural deformation, the trajectory analysis can be considerably improved. If the loads i.e. installed coefficients have not been measured by flight test, they have to be implemented either by read-across or by computational investigations under consideration of the estimated structural deformation, in terms of an angular distortion of the store in three axes.
Fig.12 shows typical read-across corrections implemented to an installed wind tunnel measured yawing moment characteristic. Here structural deformation was only substantial for positive yawing at high speeds and aircraft angle of attacks less than 5°. These corrections shown here provided a good agreement with comparable flight jettison tests which was not achievable with any other corrective terms. Another possibility for the determination of the effect of structural deformation on the initial conditions of a store to be jettisoned or released consists in computing these loads with an appropriate CFD-code.

Fig.13 documents the degree of complexity required for a corrective computational analysis. Here both missile installations are not only distorted but had also considerable geometrical asymmetries which must be represented. Such a computation provides an ideal field for overlapping techniques such as chimera codes or the DOG-method (Dynamic Overlapping Grids) presently used at DASA. The red areas of the isobarfields shown here indicate high pressures in contrast to the blue areas with low pressure.

For this theoretical analysis, the deformations have not been read across as described before, but have been directly measured during flight with a Deformation Measuring Device.
The DMD concept is sketched in fig.14. This device mainly consists of two almost identical inertial measurement units which are separately installed into the configuration. On is embodied into the store to be tested, the other unit is placed into the fuselage of the aircraft. During flight, both units are recording the mission data at their proper installation locus. These records are simultaneously referenced against the inertial navigation system of the aircraft and provide the basis for the evaluation of the structural deformations affecting the store.
The subsequently following postflight data extraction process provides a complete and accurate histogram for the time depend deformations affecting the store at each loading case during flight.
A typical result of this postprocessing step is shown in fig.15. These histograms are describing the spectrum of the angular deformation for a complete flight test mission of about 45 minutes. Each spike can be correlated to discrete manoeuvres or loading changes such as acceleration, pull-up, steady-heading sideslip, roller-coaster or wind-up turns. For the configuration selected here, the roll axis turned to be the most sensitive one with a net distortion of approximately 1.5°.
The pitch disturbance can be considered as negligibly small, whereas the misalignment in yaw of half a unit has to be taken into account. Each of these deformation terms can now be compiled in dependency of all the release parameters to be taken under consideration, and used in order to improve the data base of the trajectory analysis.

Fig.16 through 18 finally show that the consideration of the structural deformation is an indispensable part for the improvement of a store separation analysis. There, the histogrammes of the angular rates of the store have been compared with data derived from the telemetry package. It is clearly indicated that even these small deformation terms of approximately 0.5° in roll and yaw provide a considerable improvement for the lateral motion.
Looking at the commanded rudder deflections, shown in fig.19 for the above mentioned case, one can see that the deformation terms need more than the triple of the control power as required for the rigid solution.
Such improvement margins are critical for the design of a proper separation autopilot, and clearly underlines the necessity for the consideration of potential structural deformation during store separation.

4. Conclusion

- Nowadays structural deformation must be considered as an important contribution for a store separation analysis.
- If not taken into account, the deformation terms easily can deteriorate the matching process by initiating misleading corrections to a dataset.
- The risk of a separation hazard for the affected store types is considered as low, however misinterpreted corrections may result in too pessimistic limitations for the separation envelope.

- Especially for guided release or auto-piloted separation this knowledge is essential for a proper design process of the flight control system.

Although inaccessible to theory several experimental approaches and concepts provide reasonable methods for its quantification.

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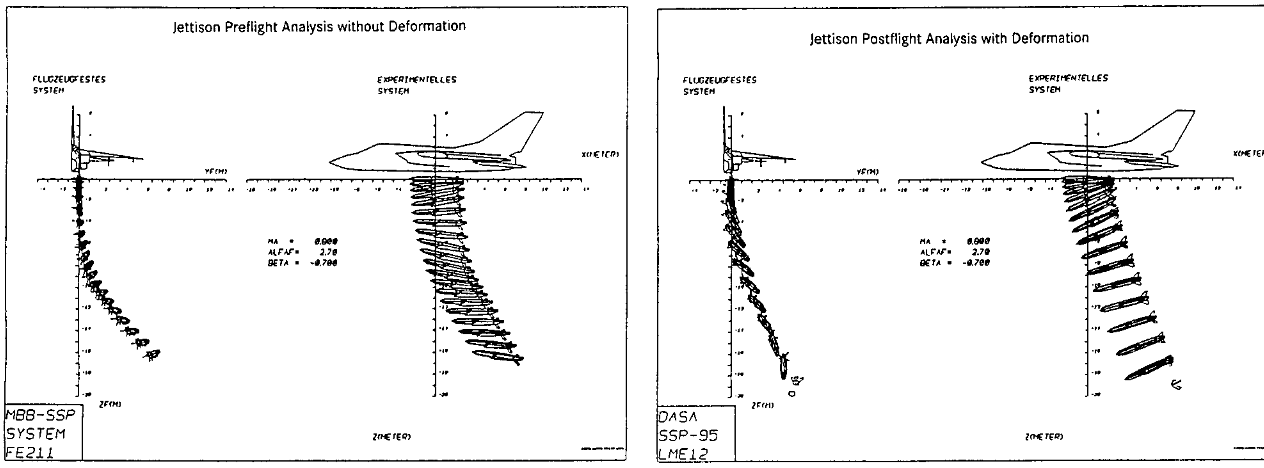

Fig. 1

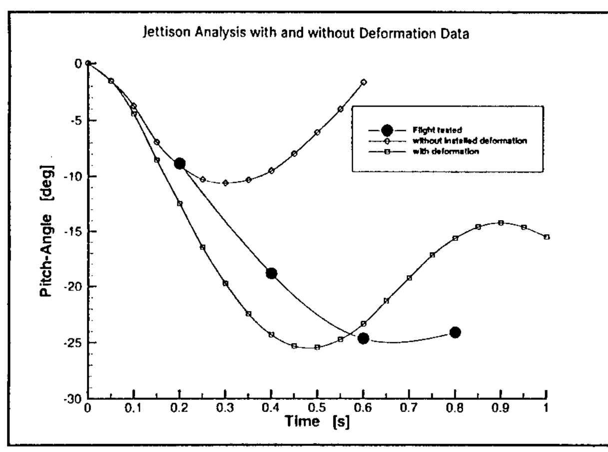

Fig. 2

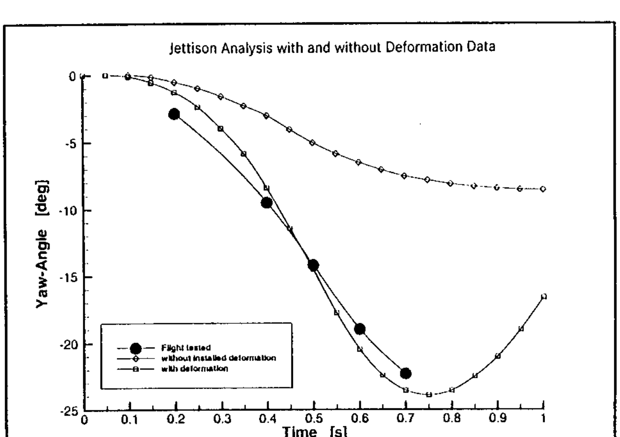

Fig. 3

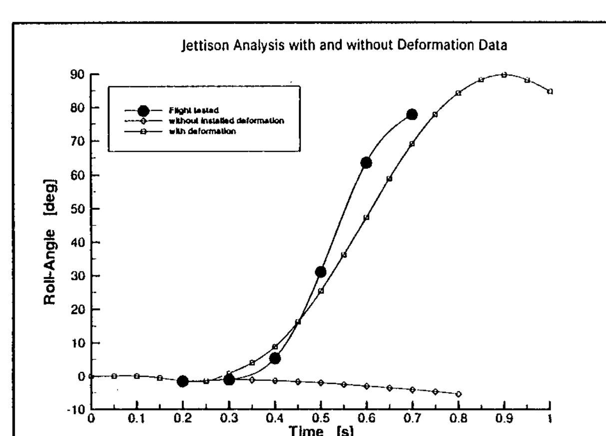

Fig. 4

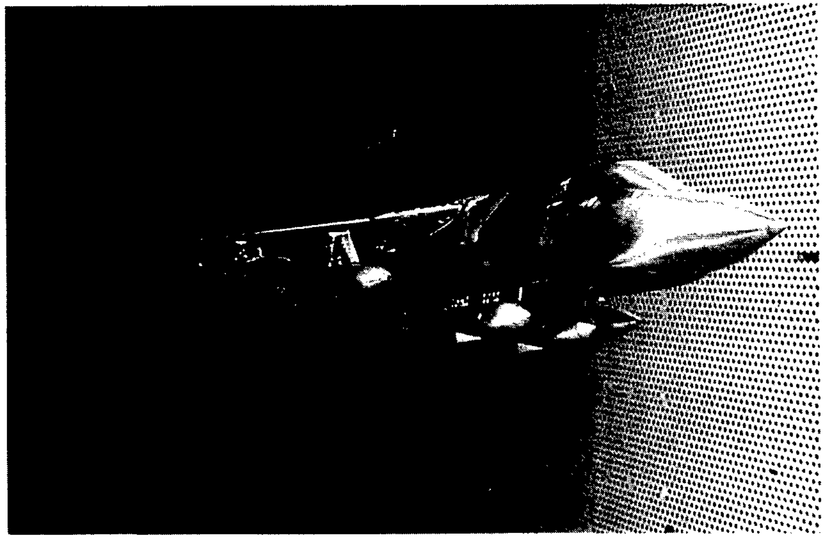

Fig. 5   WT-Test Configuration with Balanced Stores

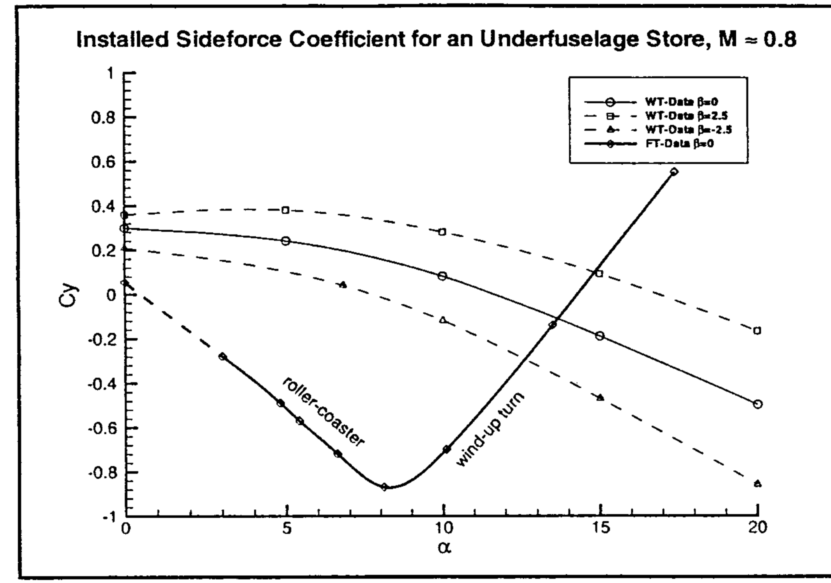

Fig. 6

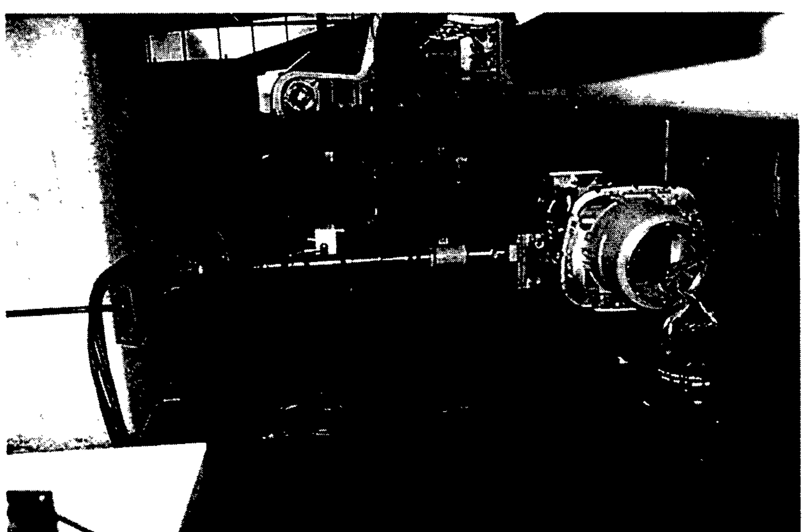

Fig. 7   Actuator Arrangement for Stiffness Test

Fig. 8   Sensor Installation for Stiffness Test

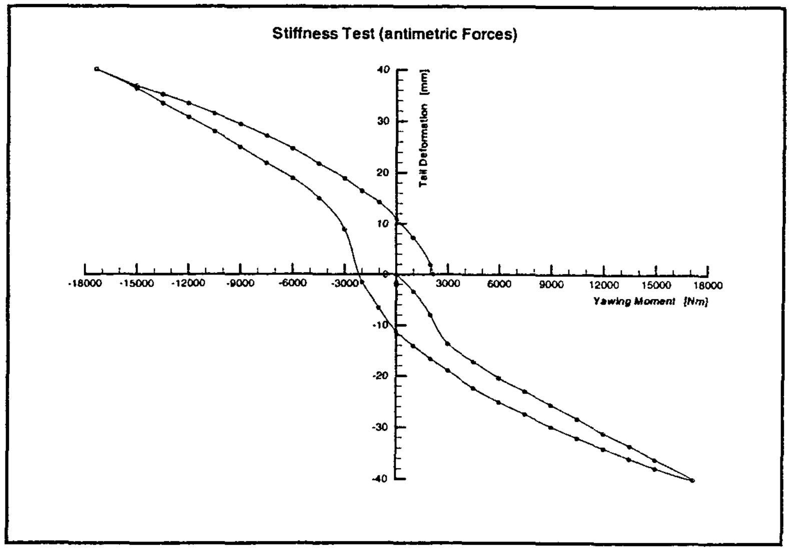

Fig. 9

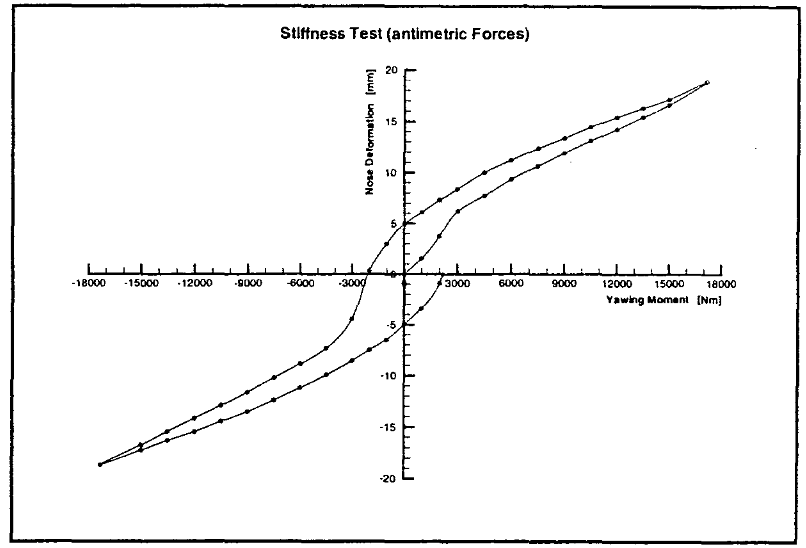

Fig. 10

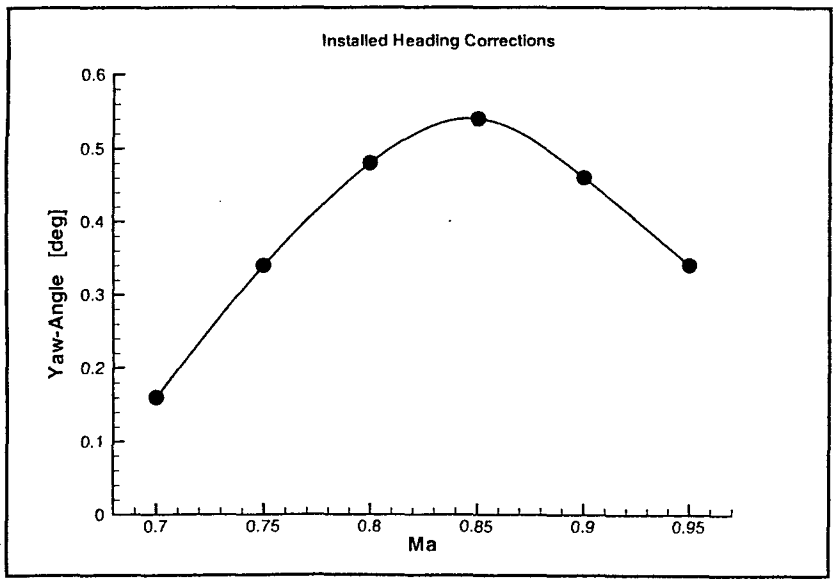

Fig. 11

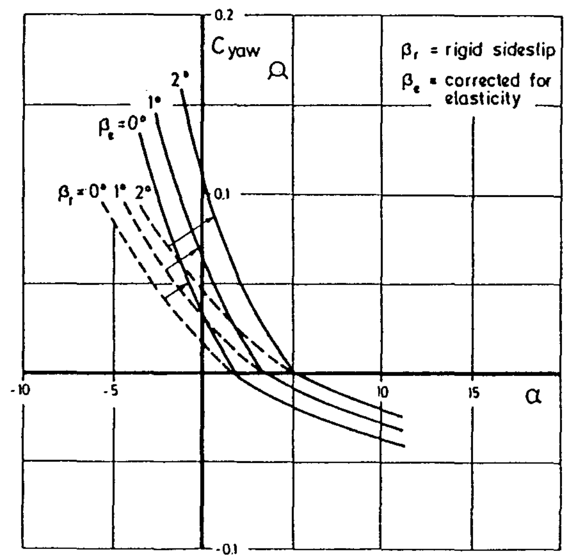

Fig. 12 Read Across Correction WT-Installed Loads

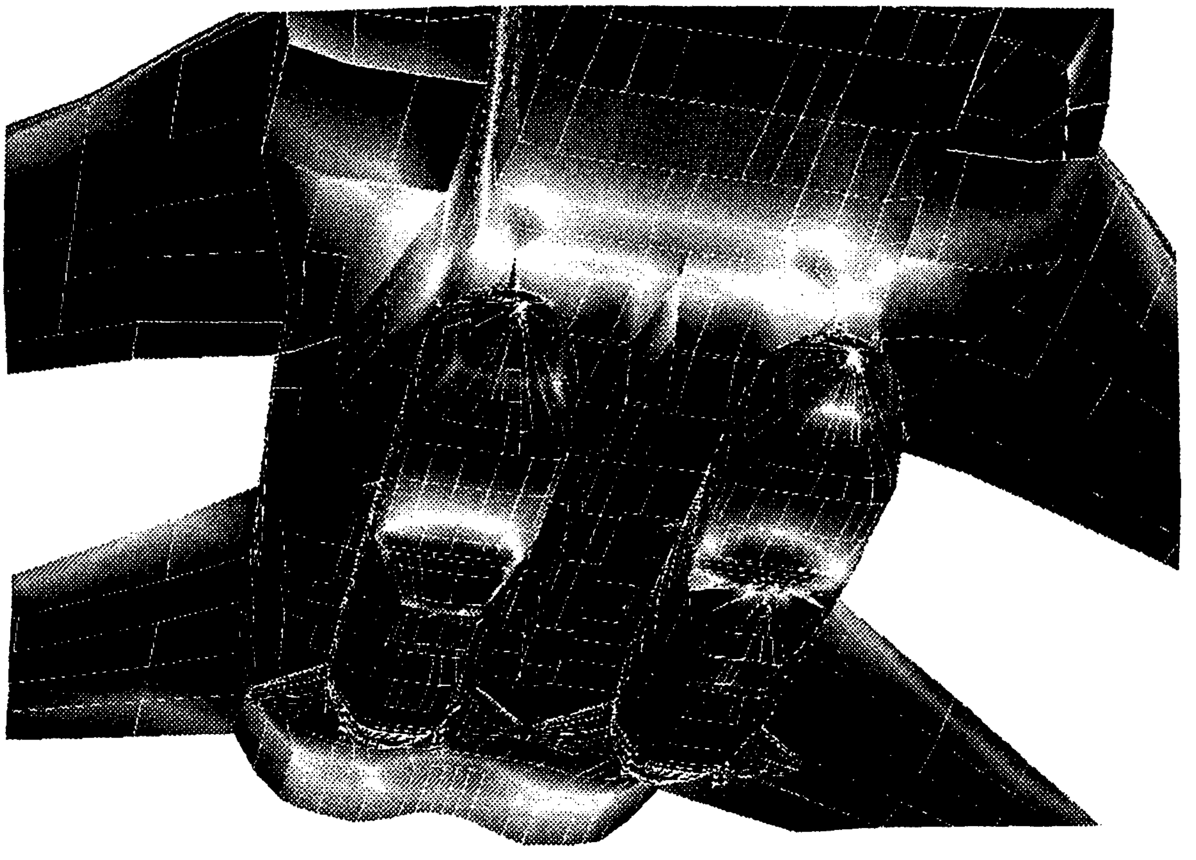

Fig. 13 DOG-Pressure Distribution with Deformation Gridding

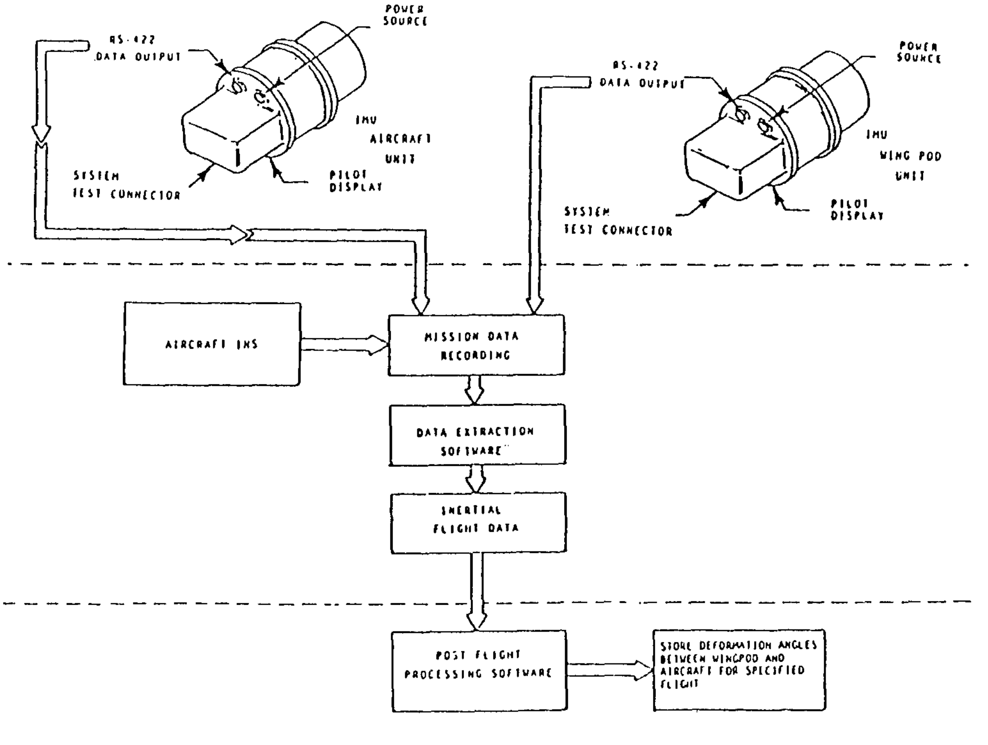

Fig. 14 Deformation Measuring Device Concept (DMD)

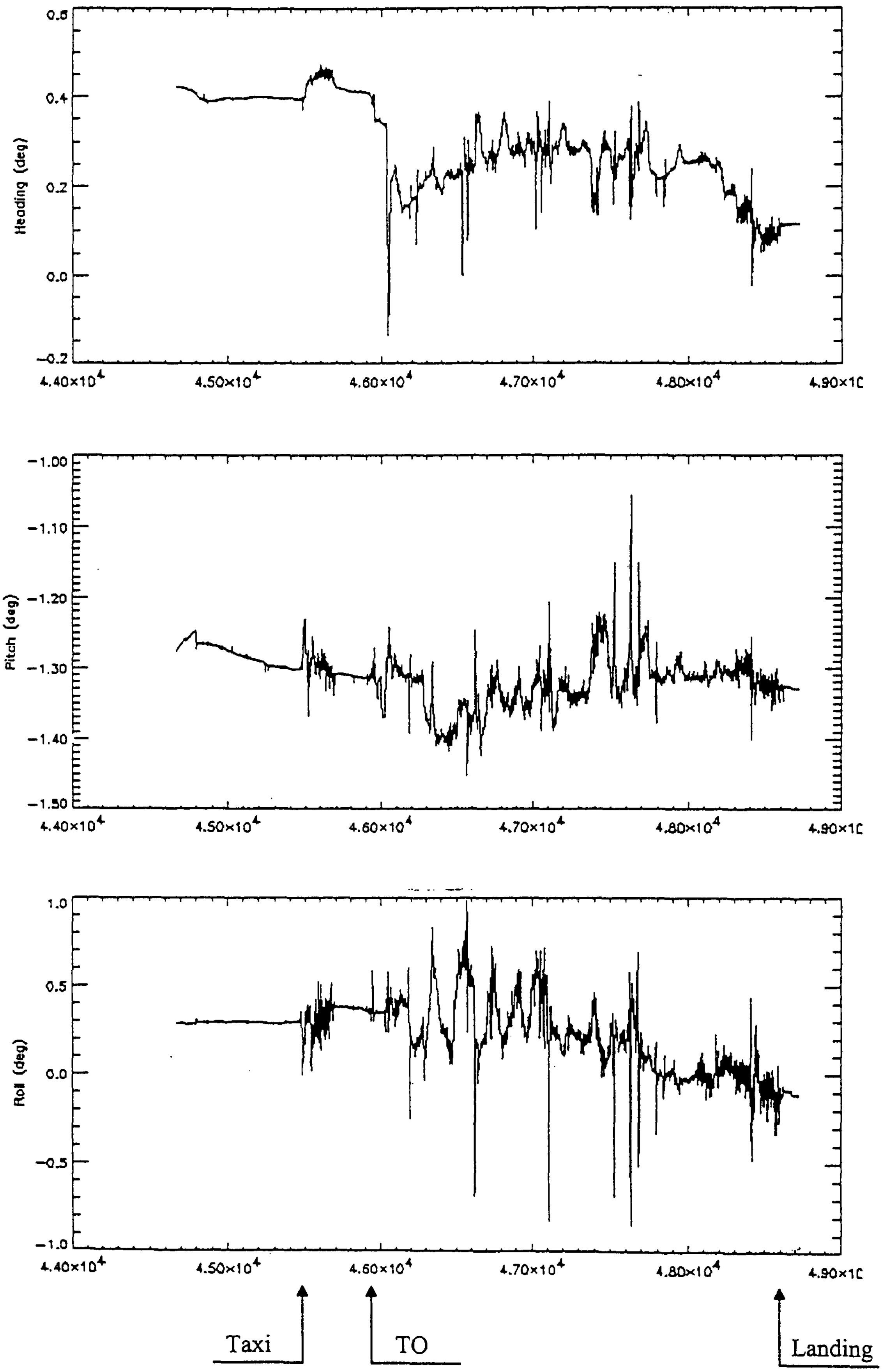

Fig. 15 DMD Results for a Completed Flight Test

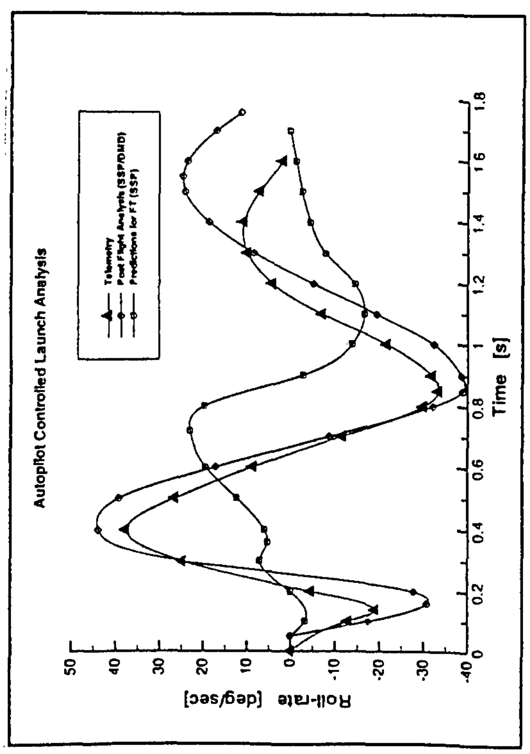

Fig. 16

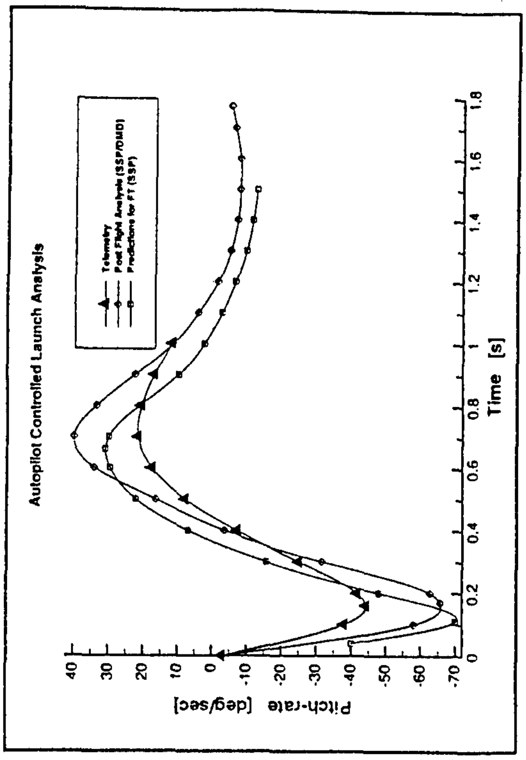

Fig. 17

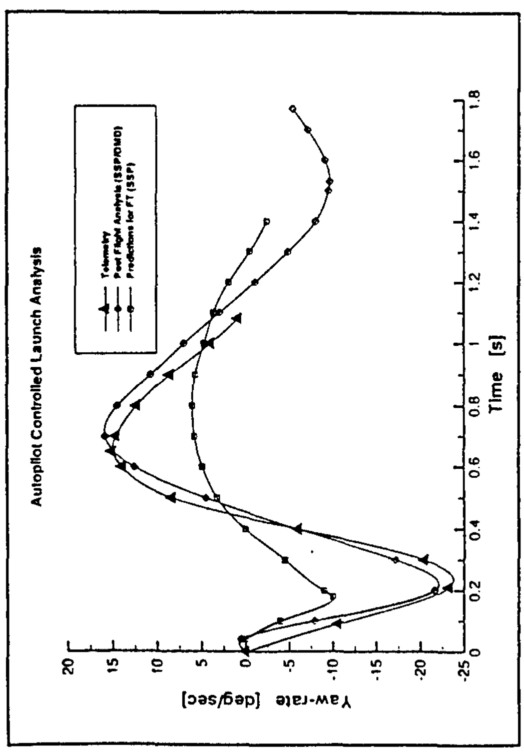

Fig. 18

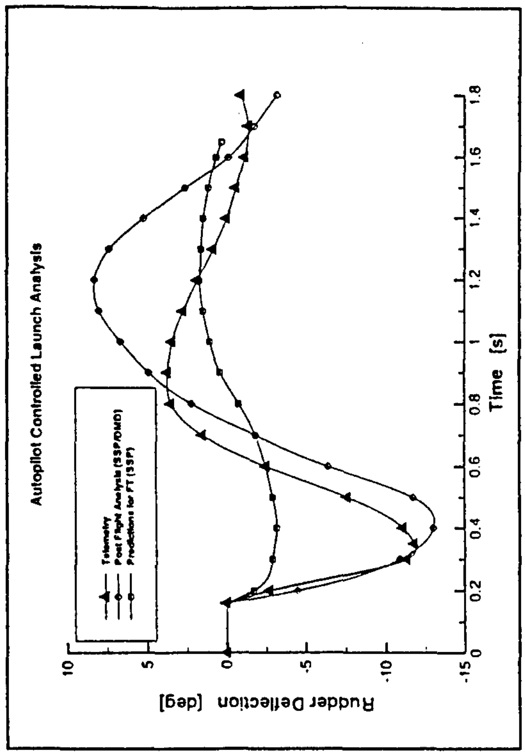

Fig. 19

A Cooperative Response to Future Weapons Integration Needs

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1. SUMMARY

As military aircraft are designed for more complex and demanding missions, integrating weapons becomes an increasingly difficult task. To address the needs of the weapons integration community, in the face of shrinking defense budgets, Air Force Research Laboratory (AFRL) has initiated national/international cooperative efforts designed to address key integration issues. The efforts are focused in three areas; integrated design/analysis software and data management, active control of weapons bay environments, and low drag, survivable external carriage options.

2. INTRODUCTION

The primary mission of military fighter aircraft is to carry and launch weapons. The desire to maintain surprise as a tactical advantage has driven modern combat aircraft design toward stealth and supersonic cruise. Because of the increasingly hostile environment in which these aircraft are required to operate, it has become important to decrease radar cross section to increase survivability. These trends have made the traditional practice of hanging dirty stores on a clean aircraft design more problematic and costly. One of the obvious needs, if one is to reduce the cost of integrating weapons, is to include weapons carriage and release issues in the weapon system design process as early as possible. This also points to the need for fast, inexpensive design tools, which at this time do not exist. These issues apply to the carriage of weapons with round cross sections, and to the release of such weapons from an aircraft flying straight and level. The constant pressure to allow for more exotic weapons and release during maneuver adds to the need for more comprehensive analysis capabilities.

Advanced, non-round weapon shapes exacerbate the store integration problem. According to a GAO Report, the Low Observable (LO) optimized Tri-Service Standoff Attack Missile (TSSAM) was canceled after the procurement unit cost rose from an estimated $728,000 in 1986 to $2,062,000 in 1994 [Ref. 1]. Part of the exponential cost escalation was attributable to difficulties in integration. According to the report, attempts were made to integrate TSSAM on a variety of aircraft platforms over an 8-year period, and not a single aircraft was certified to carry that weapon during that period. This extreme example simply illustrates that extrapolation of previous linear experience with round stores to new advanced designs is not possible, that the analysis tools to do the job are not readily available (or do not exist), and cost skyrockets as a result. The other design trend to small non-aerodynamic stores (with the same capability of much larger weapons), brings into existence a new type of store for which no integration experience exists, and which no existing design/analysis tools can handle.

Historically, the imposition of signature requirements has generally confined the carriage of weapons to internal bays, a path that is fraught with its own peculiar difficulties. Resonant acoustic modes in bays, which could be present with the bay doors open, can result in fluctuating pressure levels of sufficient magnitude to quickly fatigue and damage sensitive electronics, and aircraft and store structure. The store design trend toward smaller, cheaper, smart stores with more electronics only exacerbates this problem. Spoilers can be added to the bay leading edge to help alleviate bay resonance, but have been shown to be effective in only a limited envelope of flight conditions for any given spoiler configuration. Off design operation with spoilers has been shown, in some cases, to make the pressure loading worse. This makes the goal of internal store release under maneuver quite difficult to achieve.

With these issues as a backdrop, Air Force Research Laboratory initiated a national weapons integration planning process in April of 1996. A Request For Information (RFI) was issued to the store integration community, with the intent of finding the interests of the industry, and collecting statistics on current problems plaguing the community, as well as ideas for how to solve those problems. The response from government agencies, academia, and industry to this initial request, and the responses to an Air Force Research Laboratory questionnaire, led to a series of three meetings known as Weapons Days.

The intent of Weapons Days was to look for areas of common interest among all the participants, and to construct a process for establishing national cooperative programs in these areas. The format for the process was modeled after successful initiatives which had already been established in the laboratory's propulsion integration community [Ref 2]. During Weapons Days I (27-28 Aug 1996) government representatives from various organizations were invited to attend a series of proprietary briefings where government, industry and academia presented their responses to the RFI. After sifting through this

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

initial data, it became apparent that there were three common threads, or themes, which ran through much of the material. The first need was for tools of sufficient accuracy, which could be used in store clearance and initial design work, but which were an order of magnitude faster than conventional CFD (Euler) based tools. Combined with this need, was a desire for an integrated suite of tools which would allow for a hierarchy of analysis capability and ease of data management and storage. The second area of common interest was the integration of external stores on inventory and advanced fighter aircraft to increase mission performance and survivability. The third and final area, was concerned with active control (including controller and fluid dynamic actuator design) of the weapons bay environment, to achieve the simultaneous goal of acoustic mode suppression with safe separation characteristics.

Weapons Days II (30-31 Oct 1996) was structured as three parallel sessions (running simultaneously over a period of 2 days) reflecting the three themes from Weapons Days I. The sessions were open to all participants (not proprietary) in order to foster free exchange of ideas. National cooperative programs were launched at this meeting. Weapons Days III (2-4 Apr 1997) was an opportunity for contractors to brief specific proposals to attending government representatives. This represented the final planning and execution stage of the national cooperative efforts, where government personnel prioritized various proposals, and constructed an integrated plan which maximized use of precious resources and minimized overlap and duplication among agencies. The cooperative response to the future weapons integration needs identified in these three areas is described below.

3. EXTERNAL STORES INTEGRATION

Background

The carriage of external stores on fighter/attack aircraft has traditionally been driven by the desire to continually increase operational capability over the life of the aircraft. Currently, U.S.A.F. inventory fighter aircraft are certified to carry a plethora of stores in hundreds of different loading combinations, and the certification process continues endlessly. Each store loading combination introduces its own set of operational limitations during carriage, employment and jettison. During carriage, store loading affects maximum speed, maximum acceleration, total vehicle drag and signature, which affect mission performance, range and survivability. A typical air-to-ground loadout can easily double the total vehicle drag, which can cut the mission range in half, and can significantly increase the vehicle signature. A traditional solution to overcome these mission limitations has been to carry more fuel and electronic countermeasures, which must also be carried externally, so the cycle continues. Internal carriage may be seen as an alternative to the external carriage dilemma; however, fighter aircraft with internal carriage capability are heavier, and therefore cost more, and have less loadout capability and flexibility than external carriage aircraft.

The F-4 Conformal Carriage program, conducted by the U.S.A.F. and U.S.N. in the 1970's, initiated the search for alternate external carriage options [Ref. 3]. The objective of this program was to investigate the relative merits of conformal carriage of stores on the fuselage bottom versus conventional wing pylon carriage for several different weapon loads. Results showed that conformal carriage could increase mission radius by up to 23 percent and increase loiter time by up to 109 percent over pylon carriage. Conformal carriage also increased the maximum speed capability and aircraft roll handling qualities with stores and provided a uniform flowfield for smooth weapon separation. Obviously, weapons that have large fins and/or must be rail launched cannot benefit from conformal carriage, but this program showed that substantial performance benefits could be realized with conformal carriage for weapons that have small fins and can be eject launched.

External Carriage Technology Goals

Over the last decade, several studies have been conducted by AFRL to further research into external stores carriage options. The overall goals for these external stores integration technology development programs has been to:

- Decrease stores carriage drag
- Increase maximum velocity with payload
- Maintain or enhance safe separation
- Minimize signature degradation over clean aircraft

Cooperative Weapons Integration Technology (CWIT) Program

Starting in 1993, Wright Laboratory (now AFRL) initiated the Cooperative Weapons Integration Technology (CWIT) program to further the generic database needed to provide design guidelines for both internal and external stores integration [Ref. 4]. A generic blended wing/body advanced fighter model was designed and fabricated to enable internal and/or external carriage wind tunnel testing. The 10 percent scale wind tunnel model included a large centerline weapons bay, removable canopy (for instrumentation), a balance block for a 6 component strain gage balance and removable wings (Figure 1). For external stores testing, a nacelle could be mounted on the

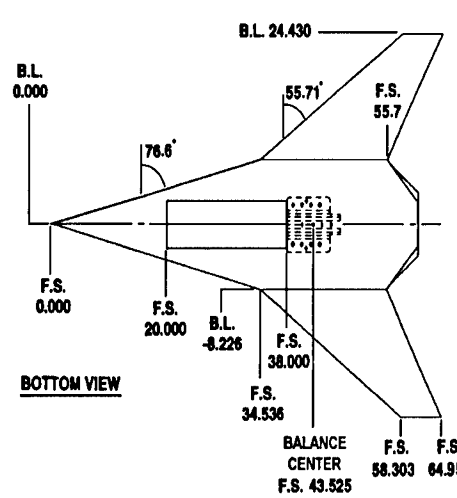

Figure 1. CWIT Generic Fighter Bottom View [Ref. 4]

bottom of the fuselage (Figure 2). Stores could be mounted to the bottom of the aircraft, the bottom or sides of the nacelle and/or the aircraft wings. The nacelle was used to represent an aircraft configuration with a chin mounted inlet (faired over), or it could also represent a low drag fuselage mounted weapons pod. The aircraft model has a full scale reference area of 597 square feet.

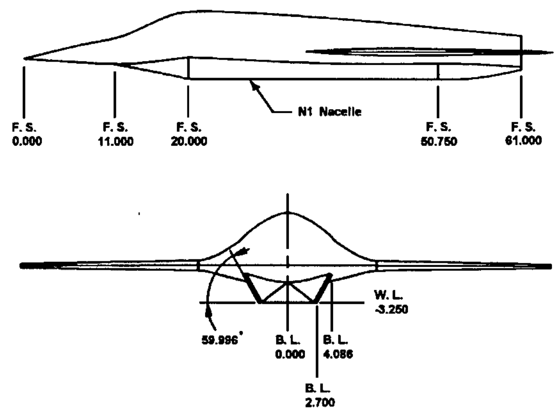

Figure 2. CWIT Fighter Lower Fuselage Nacelle [Ref. 4]

Several 10 percent scale store models were fabricated and tested during the CWIT program. The Tactical Munitions Dispenser (TMD) is the only store model described and presented in this paper. The TMD is a U.S.A.F. 1000-pound class submunition dispenser weapon which is approximately 94 inches long and 15.6 inches in diameter, full scale. The TMD has a full scale frontal area of approximately 1.35 square feet. During CWIT testing, the TMD was mounted directly to a conventional pylon in a single carriage configuration or to a multiple ejector rack (MER) like attachment on the pylon for a triple carriage configuration (Figure 3). The conventional pylon has a full scale frontal area of approximately 0.85 square feet. The

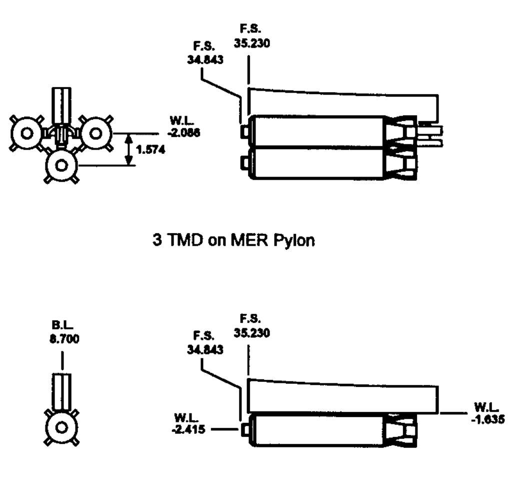

Figure 3. TMD Pylon Configurations [Ref. 4]

placement of the TMD(s) on the fuselage bottom, nacelle bottom and pylons on the CWIT wings is shown in Figure 4. Aerodynamic fairings, mounted on the nacelle bottom as shown in Figure 5, were designed to shield the TMD in two rows of three in tandem. A wing mounted weapons pod was also designed and fabricated for wind tunnel testing (Figure 6). The full scale pod would be capable of carrying a 1000 pound class weapon up to 160 inches long and 17 inches wide, and could easily carry one TMD. The wing pod has a full scale frontal area of 3.7 square feet and was mounted to the aircraft model wing at a full scale span station of 11.36 feet.

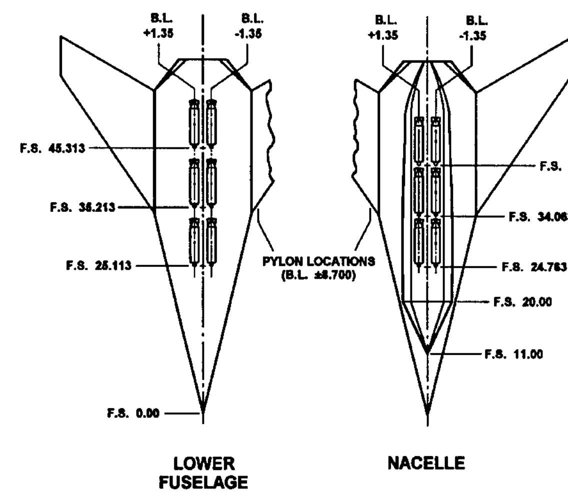

Figure 4. CWIT Fighter TMD Mounting Positions [Ref. 4]

Force and Moment Testing

The 10 percent scale CWIT wind tunnel model and external stores were tested in the Calspan 8-Foot Transonic Wind Tunnel on three separate occasions, in 1994, 1995 and 1997. The Calspan wind tunnel has an 8 foot by 8 foot cross section by 11 foot long test section with perforated walls to reduce shock waves during transonic testing. The tunnel is a continuous circuit variable density tunnel, capable of operating from .1 to 3.25 atmospheres total pressure for a maximum Mach Number of 1.35. The tunnel has a normal Reynolds number range of $1x10^6$ to $5x10^6$ per foot. For all three tunnel entries, testing was conducted at Mach numbers of 0.6, 0.9, 0.95 and 1.1 while Reynolds number was held constant at $2x10^6$ per foot.

The balance used to collect force and moment data was a Task (ABLE) 2.0 inch Mk XXXIII six component internal strain gage balance. The balance was rigidly mounted to the tunnel pitch/yaw mechanism via a circular cross section sting that entered the base of the model. The balance center was located at MS 43.25, BL 0.0 and WL 0.0 on the aircraft model. Balance cavity pressure tubes were mounted on top and bottom of the balance sting, while model base pressure tubes were routed to the blunt aft end of the aircraft model. Both base and cavity pressures were used to correct axial force and boundary layer transition strips were applied to the aircraft model and all store models to ensure a turbulent boundary layer.

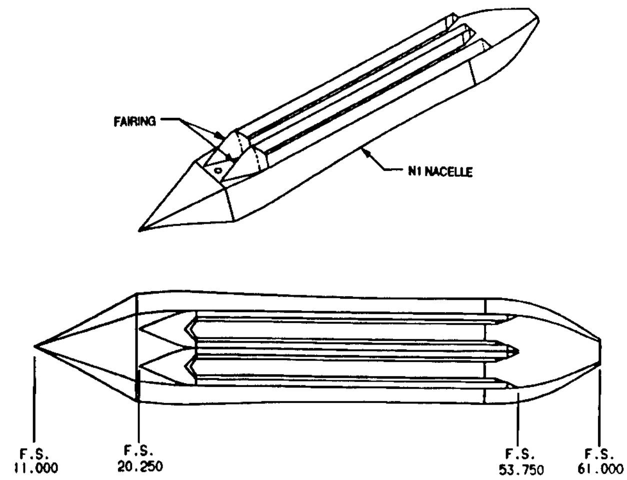

Figure 5. Aerodynamic Fairings [Ref. 4]

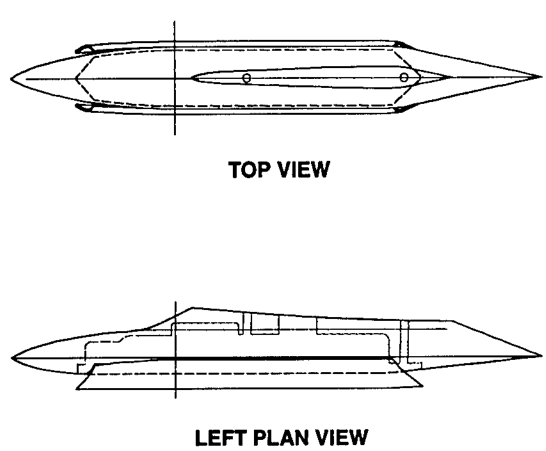

Figure 6. Wing-Mounted Weapons Pod

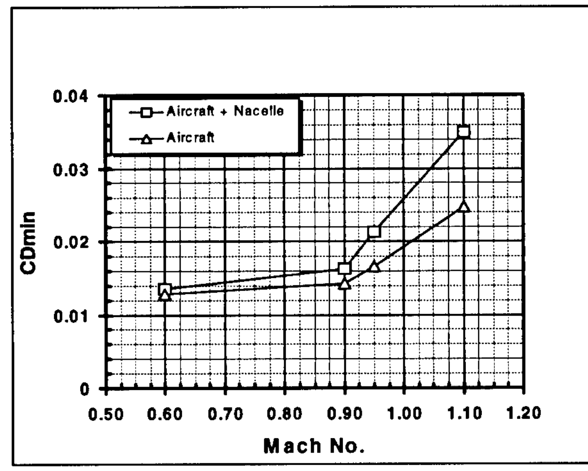

Figure 7. Baseline Configuration Drag Differences [Ref. 4]

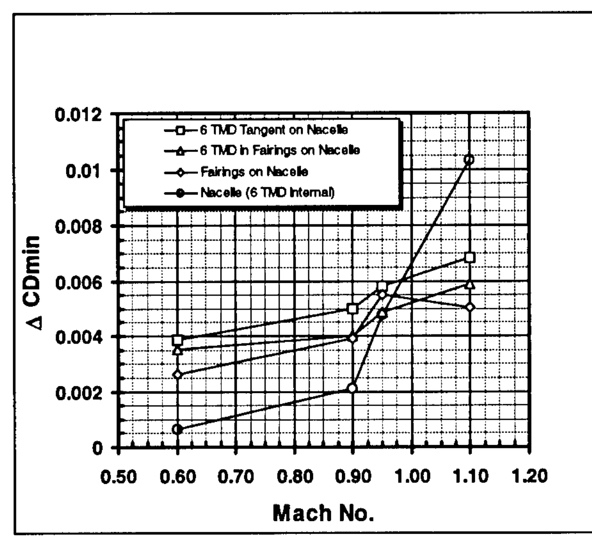

Figure 8. Drag Differences for Nacelle Tangent Carriage [Ref. 4]

Results

Baseline configuration minimum drag differences are shown in Figure 7. The aircraft only configuration exhibits a moderate drag rise above M=0.9 while the aircraft-nacelle configuration has a much larger increase in drag above M=0.9. The nacelle was designed to provide a large flat surface to mount two rows of three TMDs in tandem with fairings, but was not optimized to minimize supersonic drag.

Minimum drag differences of three nacelle tangent carriage configurations and the nacelle alone are presented in Figure 8. The tangent mounted TMDs with no fairings have the highest subsonic drag while the nacelle has the highest supersonic drag. The nacelle is large enough to fully encapsulate six TMDs but is inefficient at supersonic speeds. The fairings were designed to lower the drag of the TMDs subsonically and supersonically and, as seen in Figure 8, are successful. It is interesting to note that the empty fairings have a higher drag than the fairings with TMDs at M=0.95. The problem with the fairings is that once the weapons are dropped you still have almost the same drag, unless the fairings are made to collapse.

Figure 9 compares six TMDs carried tangentially on the bottom of the aircraft with six TMDs carried on wing pylons in two MER like configurations. Obviously, there is a substantial benefit in carrying large numbers of weapons in tandem on the bottom of the fuselage, as compared to carrying the same number of weapons on pylons. When carried in tandem, the second and third set of weapons draft the first set and contribute little increase to the drag. This effect was proven in the F-4 Conformal Carriage program discussed above [Ref. 3].

Figure 10 compares two TMDs mounted on two pylons with the wing pods. At first glance the wing pods appear to be inefficient as compared to pylon carriage; however, the wing pods were designed for carrying larger, longer weapons than the TMD. The wing pods each have a full scale frontal area of 3.7

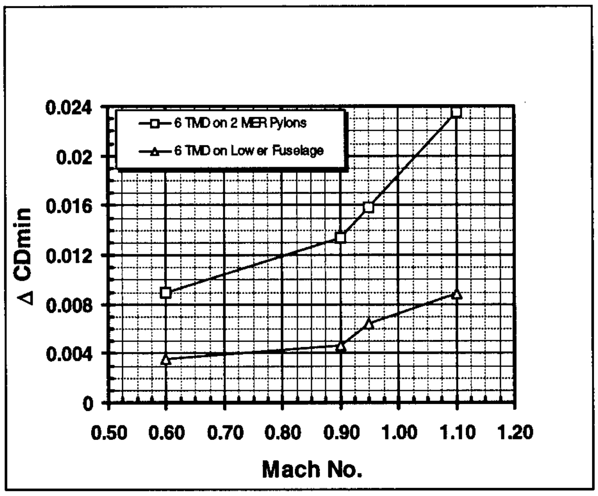

Figure 9. Drag Differences for Tangent Carriage and Wing Pylons [Ref. 4]

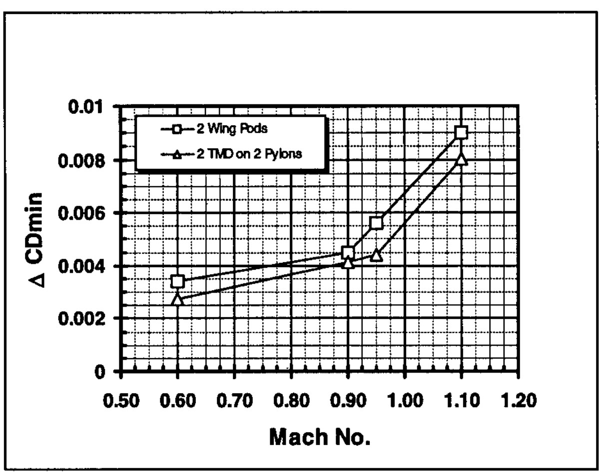

Figure 10. Drag Differences for Wing Pylons and Wing Pods [Ref. 4]

square feet and can almost accommodate two TMDs in tandem. The TMDs on pylons have a combined full scale frontal area of approximately 2.2 square feet for each set, which is only 60 percent of each pod. The drag difference between the pods and TMDs on pylons is only 12 counts (5.5 percent of the baseline) at M=0.95 and less at all other Mach numbers.

Conclusions

At subsonic speeds (M=0.6), the most efficient way to carry multiple stores is in the fuselage mounted weapons pod (nacelle), which only increases the total drag by 6 percent. All of the rest of the tangent carriage configurations increase the drag by 28 to 31 percent. The 6 TMDs on the pylons in the MER like configuration increase the drag at M=0.6 by 73 percent. The two TMDs on pylons and the pod configuration increase the drag at M=0.6 by 22 percent and 27 percent, which is less than all of the tangent carriage configurations, except the fuselage pod (nacelle).

At supersonic speeds (M=1.1), the most efficient way to carry multiple stores is in the TMD fairings, which only increase the drag by 16 percent. The fuselage mounted weapons pod increases the drag by 29 percent, while the 6 TMDs on MER like pylons increase the drag by 96 percent. The two TMDs on pylons and the wing pod increase the drag by less than 25 percent at M=1.1.

The best way to carry multiple weapons externally with the least amount of drag is clearly tangentially in tandem on the fuselage bottom. However, this is not always possible either because the weapons have large fins, which prevent tangential carriage, or the aircraft configuration is not conducive to tangential carriage. The fuselage bottom of most fighter sized aircraft have several openings and access panels for landing gear, engine maintenance, etc. To fully capture the benefits of tangential carriage, the fighter aircraft would have to be designed to carry a specific family of weapons; i.e., with small fins, and would have to be designed around such a carriage concept from the beginning.

The CWIT program ended in 1997. The success of the CWIT program, both technically and programmatically, provided impetus for the programs developed during Weapons Days and into the future.

4. ARCTIC - ACTIVE ROBUST CONTROL OF INTERNAL CAVITIES

Weapons Bay Integration Technology Goals

The traditional process of internal weapons integration has taken the path of defining the minimum required volume, designing the aircraft around that volume, and then fixing whatever problems might arise in the process of trying to certify various stores for release from the bay. The traditional option for fixing difficult separation behavior is an increase in ejection force, while the only available retrofit fix for high acoustic levels is installing a bay leading edge spoiler.

As future aircraft desire both high speed and off boresight launch capability, the need for an unrestricted weapon launch envelope becomes more pressing. Figure 11 shows the relative acoustic suppression capability of a current state-of-the-art spoiler as a function of Mach number. The figure clearly shows that at off design (at higher Mach numbers), the spoiler makes the acoustic loading in the bay worse than it was without the spoiler. This sets the stage for the need for some type of acoustic suppression, which adjusts to changing flowfield and maneuver conditions.

Spoilers have been shown to be effective in reducing acoustic loading in bays to acceptable levels. The future technology goal in the weapons bay area is to maintain suppression in the bay over the range of operation of the aircraft - not simply to achieve it at a design point of limited flight conditions. This uniform suppression over the range of operation space of the aircraft would have to also be achieved without compromising the store separation characteristics of the aircraft / store combination. This simultaneous goal would allow designers to remove unnecessary weight by 1) removing the current heavy

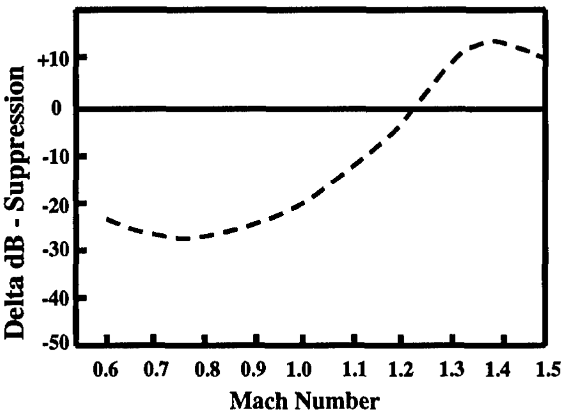

Figure 11. Variation of Passive Suppresser Effectiveness with Mach Number [Ref. 5]

spoiler and 2) designing the bulkhead and surrounding structure to see lower pressure loading. This goal would also reduce the number of smart weapons failures due to fatigue-damaged electronics. A significant side benefit would be the extended life of hardware exposed to the bay environment. Current practice is to limit the number of access panels in aircraft to reduce the number of edges requiring low-observable treatments. This trend encourages the practice of routing electronics, hydraulics, cable runs, etc. through the bay area, with the bay door serving as an access hatch. Consistently low fluctuating pressure levels in the bay would serve to greatly increase the mean time between failure for these critical exposed components, which means lower maintenance costs and more up time for the weapon system as a whole.

Background

Historically, store integrators have had limited options for certifying stores released from bays. In the past, if either the bay acoustic levels were unacceptably high for a particular store (for example, the B-43 bomb carried in the F-111, Ref. 6), or the separation behavior was not considered desirable (as in the case of TSSAM, Ref. 1), the only option was simply not to use that store / aircraft / operating condition combination. This rejection usually came after many thousands of hours of testing at a very high cost. Shrinking defense budgets will not allow for this type of situation in the future. There is the hope that by being able to actively adjust the bay flowfield, designers can both ease the acoustic loading and tailor the separation behavior.

Active Flow Control

Over the past several decades, a number of key technologies have emerged which greatly impact our ability to influence the weapons bay acoustic problem. Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), Parabolized Stability Equation (PSE) analysis, advances in computer technology, and parallel advances in experimental techniques have allowed for great insight into the nature of shear layers and their stability properties. Neural Network techniques, and other advanced control concepts have made it possible to actively control very complex, multi-dimensional systems. Finally, advances in miniaturized actuation and sensing have greatly expanded the possibilities for direct influence of local flow properties. This array of new technologies has made it possible to seriously consider active control of weapons bay flowfield as a means to expand the designers / integrators' options.

Air Force Research Laboratory has been actively involved in investigating techniques for active control in bays [Refs. 7,8]. All of the techniques to date have focused on manipulating the structures in the shear layer spanning the weapons bay cavity. By perturbing the shear layer at its most receptive point (at the upstream lip of the cavity) with some sort of vibrating actuator, the acoustic resonance in the cavity can be avoided, and the unsteady pressure levels significantly reduced. Oscillating flaps, cylinders in crossflow, piezoelectric flaps, and pulsed blowing have all been shown to achieve acoustic suppression in basic flat-plate / cavity models. In addition, oscillating flap actuators and pulsed jets have been tested in a 10 percent scale fighter model with similar results.

All of these previous results (as well as others) have been with open loop control - that is utilizing shear layer forcing at one particular frequency. Recent experiments by Cattafesta [Ref. 9] have demonstrated that both open-loop forcing and closed-loop forcing (with frequency controlled by a controller with feedback) in a cavity could reduce sound pressure levels by as much as 20dB. Figure 12 illustrates the piezoceramic driven actuator used in those experiments. Figure 13 gives a typical frequency spectra showing suppression of the dominant acoustic tone and reduction of the overall acoustic levels. The significance of closed loop control, however, is that the sound pressure level reduction could be achieved with one order of magnitude less power compared to open-loop (constant frequency) forcing. This results in significantly lower power requirements / consumption, as well as greatly increased actuator life. The experiments by Cattafesta represent the only known example of cavity control utilizing real-time phase-locked closed-loop feedback.

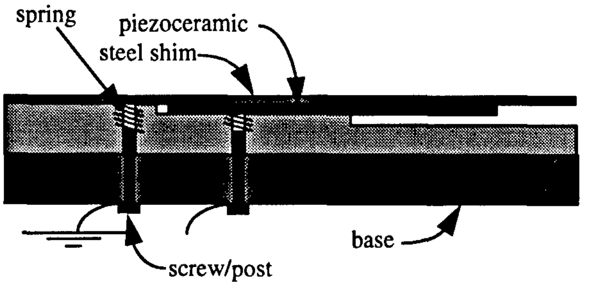

Figure 12. Piezoelectric Unimorph Actuator [Ref. 9]

With the encouraging past history of open-loop control, and the evidence from the Weapons Days symposiums that active bay control was a common concern across the industry, the consortium known as ARCTIC was created.

ARCTIC

The ARCTIC consortium was created to marshal critical mass in the bay active flow control community. By avoiding

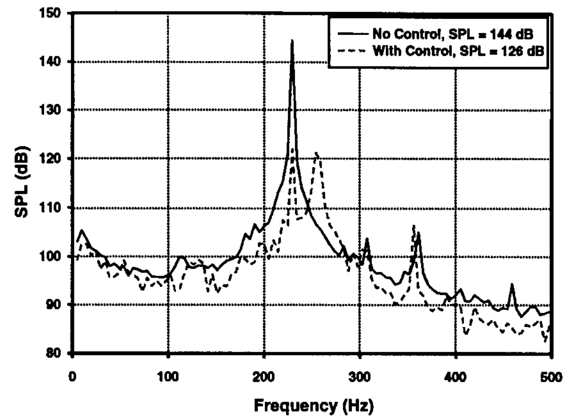

Figure 13. Amplitude Spectra of L/D = 0.5 Cavity With and Without Open Loop Control [Ref. 9]

duplication, and sharing data and experience, the participants could set more aggressive goals than would otherwise be possible.

The initial goals of the consortium are to; 1) advance promising actuation / control schemes for potential integration into a flight vehicle, 2) choose and mature the most attractive concept for flight test, 3) advance modeling concepts to aid in concept selection and design, and finally 4) to demonstrate the winning suppression concept in flight. A key tenant of the consortium is that, to transition this technology to the military user will require the demonstration of a store drop during flight test, in the presence of active control. The system will also have to buy its way onto the aircraft - it will have to show a positive life cycle cost benefit to warrant the additional complexity over simpler single point suppression designs.

ARCTIC members represent a diverse collection of organizations and interests, ranging from basic research to advanced development and flight test. Representing the large U.S. airframers, Lockheed Martin Aeronautical Systems and The Boeing Company are currently involved in maturing actuation concepts (primarily through wind tunnel tests), and developing cavity, actuator, and store separation models. Representing U.S. small business, M Technologies, Inc, High Technology Corporation, Combustion Research and Flow Technology, Inc. are providing support in the areas of smart carriage and release hardware, actuator modelling, development, and fabrication, and computational modeling of store separation with active flow control. University members include Syracuse University (shear layer impingement flow dynamics), North Carolina State University (pulsed blowing experiments and math modelling), Illinois Institute of Technology (benchmark experimental measurements and control design), California Institute of Technology (direct numerical simulation of actively controlled cavities), and Arizona State University (analytical acoustics).

Sponsoring agencies are involved in ARCTIC by supplying contracting funds, wind tunnel test time, flight test support, stores, carriage and release hardware, computational analysis, supercomputer time, ARCTIC administration, and general engineering design and analysis. Sponsoring agencies include Air Force Research Laboratory (including Air Force Office of Scientific Research, Air Vehicles Directorate, and Munitions Directorate), DoD High Performance Computing Initiative, NASA (Langley and Lewis Research Centers), Naval Air Warfare Center, and Army Missile Command. International consortium partners include Aerospace and Marine Research Laboratory (Australia), and Defence Evaluation and Research Agency (United Kingdom). The American Institute of Aeronautics and Astronautics (AIAA) supports ARCTIC through its Aeroacoustics Technical Committee, who supplies meeting rooms and special ARCTIC technical sessions at its technical conferences.

The goal of the consortium is to demonstrate active acoustic suppression in conjunction with a store release by the end of 2003. At this time, ARCTIC members are concentrating on developing a large set of options for active suppression (encouraging healthy and honest competition) with the hope that an obviously superior candidate will emerge. ARCTIC is also funding the development of analysis tools to refine actuation designs and control algorithms, and to clear stores for release during flight test. Once the concepts and tools are in place, the expectation is that one of the U.S. airframers will act as prime contractor to take a concept to flight test. Part of the role of the prime contractor is to conduct system studies and cost tradeoffs to ensure that the new active system provides a significant improvement to current practice and improves overall weapon system effectiveness.

Advanced ARCTIC Concepts and Considerations

It is clear that within an association as diverse as ARCTIC there is a wide range of maturity among the actuation concepts, and that the consortium will have to freeze a design at some point to do the necessary integration work for flight test. Some of the current concepts hint at the possibility of suppression levels as high as 30 dB [Ref. 7], but may not be sufficiently mature in time for a 2003 test goal. Attractiveness of the advanced concepts and interest of the consortium members will dictate whether any concept development continues beyond a planned 2003 flight test.

One can sketch out the characteristics of an optimal system, by studying the characteristics of the current one. Leading edge spoilers typically provide not only a minimum level of acoustic suppression, but also provide improved store separation characteristics over bays without spoilers. If the new system is to replace (i.e. remove) the existing spoiler, provision must be made to replace the current spoiler separation enhancement. Without this consideration, stores that were cleared for release on current inventory aircraft would have to be requalified on the new system. This is the rationale behind requiring that separation concerns be considered up front before committing to a design for flight test, and why ARCTIC members are dedicated to the total weapons bay integration solution.

When one considers the problem of separating a store from an internal bay, there are two ways to approach the problem. One can to accept the flowfield that was inherited from the aircraft designers, and attempt to overcome the generally poor separation tendencies through high ejection velocities. The "g"

loading resulting from this practice is sometimes unacceptably high (on either the store or aircraft), and integration fails. The other approach is to modify the bay flowfield to make it more weapons friendly.

As we have mentioned, a leading edge spoiler is a device which, in addition to providing acoustic suppression, modifies the bay flowfield to provide a positive separation environment. But this is only one technique. Obviously, adding (or subtracting) mass, momentum, or energy to the flowfield by other means can also achieve a beneficial separation flowfield. ARCTIC has only begun to investigate this aspect of the total weapons bay problem.

With this background, the optimum ARCTIC system would have the following characteristics: independent control of the separation environment and acoustic field, low cost, ease of maintenance, reliability, low weight, and be retrofittable on existing aircraft. Independent control of separation characteristics would allow designers to optimize both acoustic levels and separation characteristics, and to adapt the active control package to changing launch conditions and to different store loadouts. The key to a truly advanced internal store integration capability will be actuation techniques which provide some degree of independent control of these two effects.

5. A/SIM - ALLIANCE FOR STORES INTEGRATION METHODS

Background

Traditionally, the wind tunnel has been the tool for test and evaluation of developmental aircraft/store configurations; and flight testing has been used for store certifications. Analytical methods, based on various types of Computational Fluid Dynamics (CFD), have to date had only a limited impact on the aircraft-store certification process. Significant compromises in the modeling often are needed to obtain CFD results in a useful time frame or at an acceptable cost. These compromises are clearly recognized and they are qualitatively understood, but their impact on the quantitative predictions usually can only be guessed. Therefore, CFD methods generally are used only to provide general understanding and to pre-screen certain aircraft-store-flight condition combinations to identify the critical cases in guiding subsequent wind tunnel and flight testing. In today's environment, affordability is a very real concern. The cost of store certification is a substantial portion of the life cycle cost. Hence, necessity to reduce cost has driven both government and industry organizations more and more toward numerical analysis.

Individual efforts of the DoD services, NASA, contractors and academia, have provided a host of prediction methodologies for evaluating aircraft/stores integration and separation. Prediction methods in use today range from low-order empirical, semi-empirical and analytical methods to high-order computational fluid dynamic simulations. Unfortunately lower order methods are very case dependent. Most are based on axisymmetric weapon designs which may not reflect the current trend toward more survivable designs. For carriage configurations, the panel method is the quickest to set up and compute, however, at transonic speeds and complex maneuvers, is often not appropriate. Increasing the fidelity of the physics to Euler and Navier Stokes simulations brings about uncertainties regarding gridding, computational time, and turbulence modeling for the case of viscous analysis. Using these same methods for computing the time-dependent near-field/trajectory problems involves the use of reconfigurable meshes and prediction uncertainty management techniques which are state-of-the-art or even beyond state-of-the-art at this time. Some of these developments are being addressed in other technology programs. For internal carriage, both the acoustics and the separation characteristics of the store must be considered. Rossiter's equation [Ref. 10] and other useful design tools are used to establish the resonance frequencies; however, even complex Navier Stokes calculations have difficulty capturing the amplitudes of the acoustics inside the bay. Currently, the weapons integration community is evaluating the state-of-the-art computational ability to simulate the acoustics and separation characteristics of weapons bays.

While the ability does exist to compute specific design points with complex numerical analysis, even with the increase in computing power we have seen in the last decade, it is still not feasible to use these methods for preliminary design or for stores certification. These tasks require timely analysis of many configurations and flight points. Hence, a suite of enhanced state-of-the-art tools is needed for the stores integration community to aid in design, analysis and certification. These tools should range from established data bases and handbook correlation to neural network technology and CFD analysis. Whether, data is generated in a wind tunnel, flight test or through numerical analysis, there also is a need to manage the information such that it can be used for design guidelines, validation of methods and clearance by analogy.

Alliance Organization and Goals

In today's climate, with declining budgets and more emphasis on collaborative efforts, Air Force Research Laboratory led the formation of a joint alliance to coordinate tool development efforts for the store integration and certification community. The membership of this alliance is shown in Figure 14.

The primary focus of A/SIM is aerodynamics and aeroacoustics, with the potential for growth into multidisciplinary applications. Specific objectives of A/SIM are to promote technical interchange and transfer, develop prediction methodology, develop validation and verification benchmarks, provide a government expert advisory resource, reduce system life cycle costs and foster cooperative research and development programs (see Figure 15).

The management structure of A/SIM consists of four interrelated groups: Government Executive Committee (GEC), Government Advocacy Group, Industry/Academia Advisory Committee, and Technical Working Groups (TWGs) (see Figure 16). The GEC is responsible for the operation of the alliance and the translation of guidance from the Government Advocacy Group and recommendations from the Industry /Academia Advisory Committee (IAAC) and Technical Working Groups into long term road maps. It is composed of representatives of tri-service government agencies involved in

stores development and integration. The IAAC and Government Advocacy Groups consist of executive level representatives that assist in developing road maps and provide industry and government perspectives on requirements. The technical working groups are formed as required to cover particular technical topics of interest. Collectively, the TWGs identify and prioritize critical technology development areas and make recommendations to the GEC.

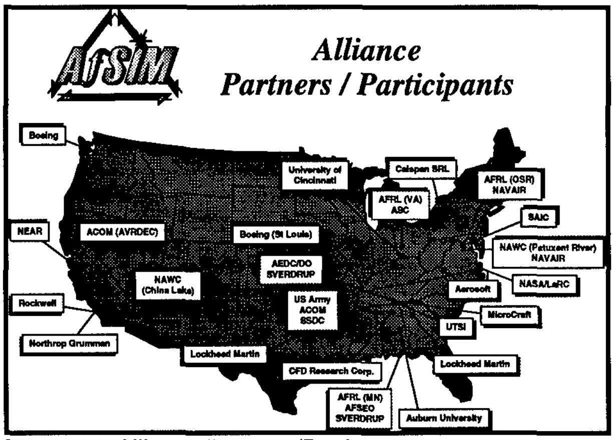

Figure 14. Alliance Partners/Participants

Technical Working Groups
At the present time, there are three technical working groups within A/SIM: Database Management, Validation, and Uncertainty Analysis.

Database Management
The database management technical working group is focused on using neural network technology for advanced information

Promote Technical Interchange and Transfer
- ! Encourage technology transfer between Industry, Government, and Academia
- ! Create a forum for exchange of technical information in weapons integration and separation technologies and the discussion of common concerns and interests pertinent to DoD applications

Develop Prediction Methodology
- ! Develop and/or refine design and analysis techniques which incorporate basic engineering methods, experimental data and modeling and simulation for the prediction of stores carriage loads and separation behavior
- ! Establish a procedure for disseminating information including points of contact for methods covered by the alliance.

Develop Validation and Verification Benchmarks
- ! Develop and maintain nationally recognized standards, data, and procedures for validation and verification of analysis techniques, and the application of this technology to DoD systems

Provide a Government Expert Advisory Resource
- ! Provide the DoD acquisition and research, development, test and evaluation (RDT&E) communities with expert advisory resources for test and evaluation of operational and developmental systems

Reduce System Life Cycle Costs
- ! Minimize the amount of wind tunnel experiment and flight testing through the increased use of analytical and/or numerical methods
- ! Exploit prediction methods for preliminary design, retrofit, mission planning, and stores certification analyses

Foster Cooperative R&D Programs
- ! Coordinate tri-service R&D requirements
- ! Conduct technology development programs in areas of common interest
- ! Execute joint procurement actions for economy of scale

Figure 15. Alliance Goals

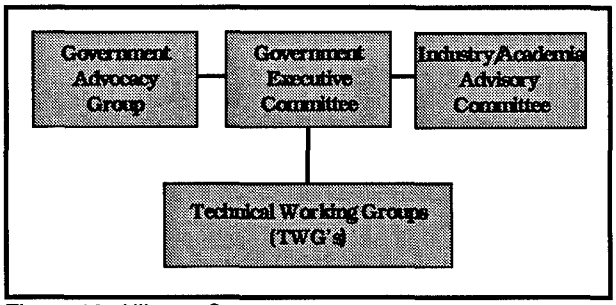

Figure 16. Alliance Structure

management of stores integration data. The feasibility of using neural networks for ballistics, store aerodynamics, grid surveys, and store trajectories is being investigated. An A/SIM Phase I feasibility study completed in March 1998 under U. S. Air Force funding demonstrated that neural networks can accurately reproduce the five force and moment coefficients associated with the AIM-120 released from an aft fuselage station on the F-15 C/D. The neural network approach reduces the amount of data that need be stored for trajectory calculations. Specifically, for the feasibility study 170,000 values of each force/moment coefficient were to be reproduced by approximately 500 network weights. Moreover, neural networks provide a means for accurately interpolating a nonlinear function between input values as compared to linear interpolation generally used in conventional trajectory calculations.

The Boeing Phantom Works code GENNET was successfully used to generate neural networks that accurately reproduce wind tunnel force and moment data measured for the AIM-120 in the F-15 C/D flow field. The original data were augmented by Lagrange interpolation to ensure the data adequately covered the input space. Using two hidden layers with 20 nodes/layer and 20,000 cycles of training, each force and moment coefficient was reproduced within r.m.s. error of 10^{-3} as functions of angle-of-attack, Mach number, and geometric locations in the flow field.

In all cases the neural network provided a reasonably smooth curve through the wind tunnel data. Representative plots of the results for normal force and pitching moment are shown in Figures 17 and 18 respectively. The lines represent the neural neural network model and the symbols are the data. This curve readily provides a nonlinear interpolation between the actual data points. Traditionally these test data would be loaded into tables that would be interpolated linearly for intermediate values. Taken as a whole, the neural network seems to offer an improved representation of the data base.

This feasibility study established the utility of using neural networks to condense a large store separation data base. It is recommended that future work be pursued to expand the number of input variables and use the results in combination with a six-degree-of-freedom program to compute store trajectories. The latter could be compared with trajectories obtained using alternate techniques with regard to accuracy and required computing time. During Phase II this is exactly what is being planned. This effort (just now underway) will build on the initial feasibility study of the F-15/AIM-120 database and train neural networks for two additional data bases to be

selected by the U. S. Air Force from the following options: 1) The MK-82 LDGP and CBU-87 weapons for station LC3 on the F-15E or 2) Two weapons at the same station for the F-16. Neural networks will be trained for the data bases and coupled with a six-degree-of-freedom trajectory program to compare the results of store jettison trajectories obtained using neural networks with those obtained using a standard table-look-up approach. A comparison of trajectories and of associated computer time and storage requirements will be made. In this effort, consideration will be given as to how weapon characteristics (such as mass or geometric properties) can be included as input to the network.

Validation

There is a high demand for validation data for numerical simulations. There is equally a desire in the test and evaluation community to compare the results of various algorithms and techniques. Given the advantages to be gained through the utilization of separation predictive methods and the growing need for such predictive capabilities in the development and certification of emerging weapon systems, it is imperative that such capabilities continue to be developed, evaluated and thoroughly understood. The technical community must be able to select the method or methods best suited to a given situation. Therefore, the capabilities and limitations of the various predictive methods must be determined and clearly understood. Such an evaluation and understanding also provides for identification of situations for which the available predictive methods are inappropriate or are not of sufficient fidelity.

In response to the current limitations on DOD research, development and acquisition budgets, it is apparent that modern separation prediction methods must be leveraged to reduce the resource allocations required to develop and certify new

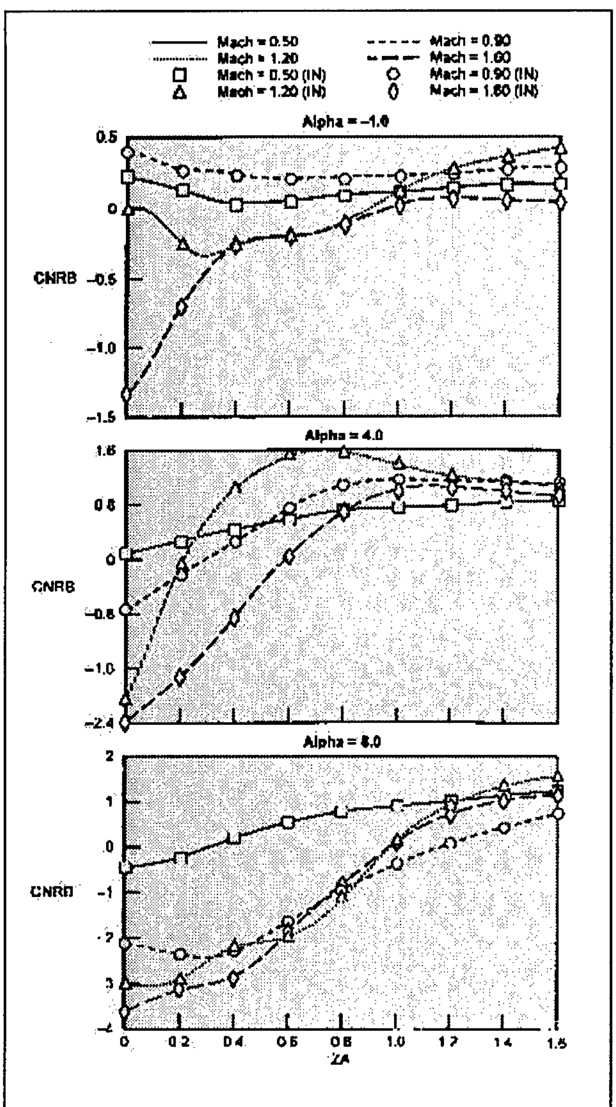

Figure 17. AIM-120 / F-15 Normal Force (Symbols are Data, Lines are Neural Network Model)

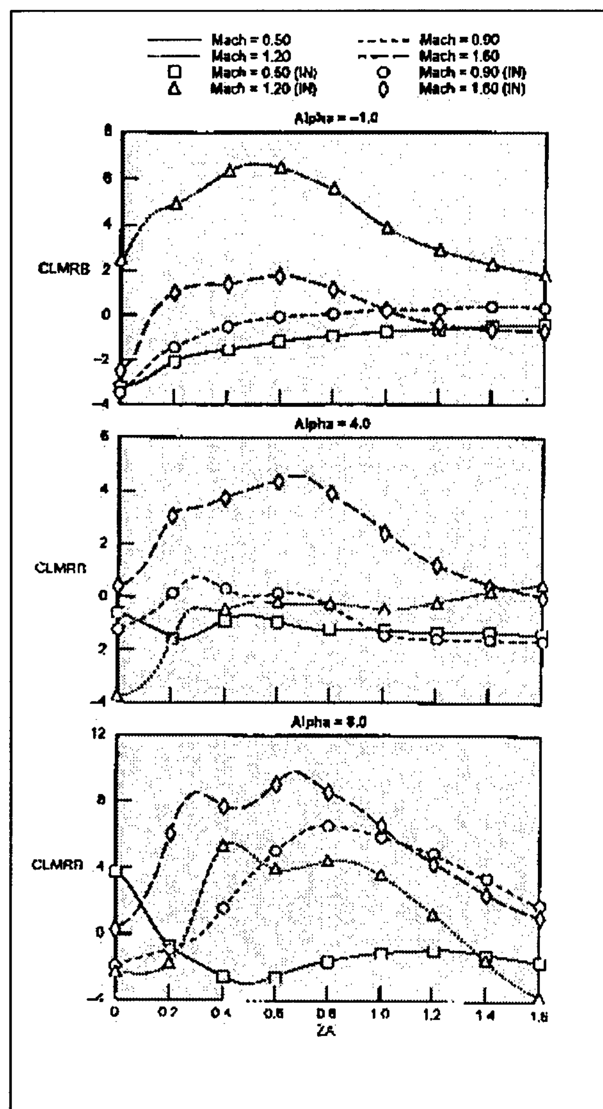

Figure 18. AIM-120 / F-15 Pitching Moment (Symbols are Data, Lines are Neural Network Model)

weapon systems. These methods can be utilized in the earliest stages of development to identify store separation problems and initiate cost effective corrective actions. Later in the development cycle, predictive methods can be utilized to tailor the testing efforts. When such methods are utilized in conjunction with flight testing, the selection of test event scenarios can be made more effectively, thereby reducing the overall number of test events required. The flight test results, in turn, further validate the predictive methods and increase their fidelity. Once the predictive methods are fully validated through flight testing, they become an invaluable resource in completing the certification process. This is especially important for the emerging small smart munitions, such as SSB and LOCAAS, due to the increasingly large number of separation scenarios generated by the carriage of a large number of these munitions. Relying primarily on flight testing to certify such munitions would be a formidable and costly proposition indeed.

As part of A/SIM, an assessment of the accuracy of various trajectory prediction methods is being performed. It includes the prediction of trajectories for a Mk84 JDAM released from an F/A-18C at two flight conditions. This is an extension of the joint WMASC ACFD/AIAA F/A-18C JDAM CFD Challenge issued by the Navy, but to include non-CFD based methods. The predicted trajectories will be compared to wind tunnel and flight test data sets provided as part of that challenge, including examinations of trajectory time histories, force and moment predictions and estimated flow field characteristics.

In addition, a survey to assess the level of accuracy that trajectory prediction methods must achieve to allow a reduction in the number of flight tests required to certify stores for operational use is also underway. The relative importance of the trajectory characteristics and a rating scale based on tolerance levels will be established based on input from potential users. The inputs are aimed at defining a set of common safe separation criteria. The results of the prediction methods assessment described above will be used to establish the methods ratings. These prediction method ratings will be compared to a similar set of ratings developed for typical flight test programs. And finally, a set of fidelity recommendations will be developed and documented.

Uncertainty Management

Closely coupled to validation is the measurement of uncertainty. Many data sources are available to contribute to the goal of predicting store carriage loads, safe separation and ballistic accuracy. These methods differ widely in both cost and accuracy. Therefore to have a balanced view of the merits of each method, we must gain an understanding of the impact of aerodynamic data uncertainty and the sources of uncertainty. Using this understanding, the community can intelligently assess the results of validation studies and choose from among the various methods and data sources for a particular application. It seems clear that, with adequate confidence in predictions, the cost and time of the store certification process can be significantly improved through reductions in the scope of wind tunnel testing and flight testing needed to gain confidence in the compatibility of specific aircraft-store combinations. Most importantly, the risks of store certification flight testing will be greatly reduced based on full knowledge of potential risks.

One key step toward this goal is to be able to estimate the uncertainties in CFD-based store separation predictions in specific applications, both before and after the analyses are performed. Pre-analysis uncertainty estimates will enable the most cost-effective analysis tools to be selected for the purpose at hand, and will enable the buildup of a store certification testing plan for cases where test rather than analysis is the most cost-effective approach to reduce risk. Post-analysis uncertainty estimates will enable confident determination of the level of trust which can be placed in a specific CFD analysis.

Towards this end, A/SIM is conducting a study which will select a representative class of problems to be used in demonstrating the value of uncertainty management based on Belief Functions in support of assessments of safe separation. This selection shall include aircraft and store configurations,

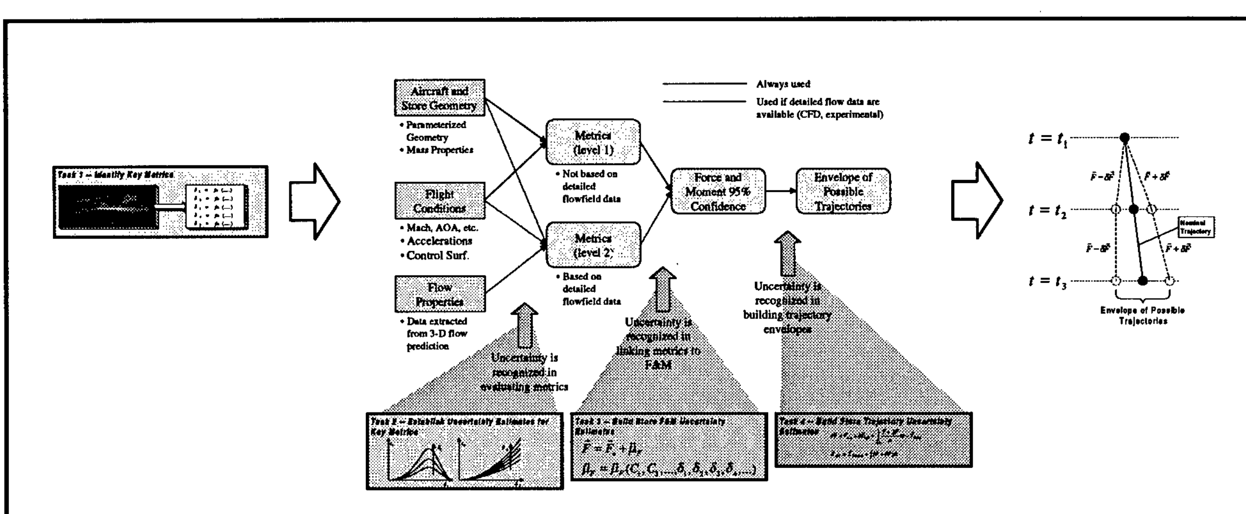

Figure 19. Approach to Uncertainty

flight conditions, and level of CFD modeling to be used. A set of metrics to correlate CFD prediction uncertainty for store forces and moments, within the selected class of problems; and models of the store force/moment uncertainty associated with each of the selected metrics will be generated. A Quality Function Deployment (QFD) approach will be utilized to determine the relative importance/influence of each factor on the resulting separation characteristics. Then the effort will integrate these models to build combined estimates of the uncertainties in store forces and moments at discrete points along the store trajectory, from the store carriage condition to the point along the trajectory where safe separation is assured. This in turn will be used to build an envelope of possible trajectories, based on the estimated force and moment uncertainties, in assessing the safe separation of the store throughout its trajectory. The process is illustrated in Figure 19.

6. CONCLUSIONS

Future weapons integration needs for military aircraft have been identified. AFRL has initiated three national/international cooperative programs to address these needs. These programs are; Cooperative Weapons Integration Technology (CWIT), Active Robust Control of Internal Cavities (ARCTIC) and Alliance for Stores Integration Methods (AfSIM). This cooperative response to these future weapons integration needs will lead the weapons integration community into the 21st Century.

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LE ROLE DU MISSILIER DANS UNE INTÉGRATION D'UN MISSILE TACTIQUE A UN AERONEF
EXEMPLE DU PROGRAMME 2000-5

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1-RÉSUMÉ

La complexité des systèmes d'arme modernes, tant du point de vue du missile que de l'avion a fait de l'adaptation d'un missile à un avion un programme à part entière, à coût élevé et découplé du développement du missile proprement dit.

Chez Matra BAe Dynamics le programme d'intégration est géré par une équipe distincte de celle qui s'occupe du développement du missile à proprement parler.

On verra que pour mener à bien un tel programme la participation du missilier est nécessaire très tôt, car il intervient dans les premières études de concept d'emploi de l'arme, de part sa connaissance du missile et son expérience dans des adaptations antérieures.

Le fait d'utiliser de plus en plus de simulations numériques, tant dans le cours du développement, qu'en finale pour démontrer l'ensemble des performances, renforce la nécessite de sa présence aux côtés des autres industriels majeurs du système que sont l'avionneur et le radariste.

On verra enfin que confier au missilier le développement des équipements d'interface est un facteur de succès, dans la mesure ou l'optimisation de l'interface Lance-Missiles/missile, la plus critique sur le plan aéromécanique, s'en trouve facilitée.
Ceci est particulièrement vrai dans le cas d'un missile air-air.

2. LES ORIGINES DU SYSTÈME MICA/2000-5

2.1. Un besoin

Face à la menace de raids massifs, l'avion de chasse doit disposer d'une puissance de feu maximale, utilisable par tous les temps , et d'une capacité de traitement simultané de plusieurs cibles.

2.2. Des opportunités / un concept

Dès le début des années 80, l'idée s'impose en France que la miniaturisation des équipements électroniques permettrait de réaliser des missiles Air-Air d'interception à moyenne ou longue portée beaucoup plus compacts et légers que ceux alors en service, et de les doter de la capacité combat.
Qu'en conséquence on pourrait emporter un plus grand nombre de ces missiles sous un avion de taille donnée et qu'il faudrait disposer, pour mettre à profit cette puissance de feu nouvelle, d'un radar adapté, de commandes et visualisations nouvelles, offrant au pilote une vue synthétique de la situation, lui proposant des choix pertinents tout en lui laissant la possibilité de décider de les accepter ou de les modifier.
Enfin, le missile, pour pouvoir être emporté en nombre sous l'avion sans en grever les performances, devait pouvoir être éjecté ou tiré sur rail.

2.3. Les développements exploratoires (D.E.)

Afin de conforter ces convictions, et pour limiter les risques, une série de développements exploratoires furent lancés pour valider :

- le pilotage par déviation de jet ,
- le guidage biphase (guidage inertiel puis autoguidage),
- le principe extraction/éjection qui préserve une interface mécanique unique du missile vis à vis du Lance-Missiles ,
- l'acquisition et la poursuite simultanée de plusieurs cibles par un radar, l'élaboration des désignations d'objectifs correspondants par l'avion, leur transmission au missile sous avion avant tir, puis en vol via une liaison hertzienne dédiée, dite "LAM" pour Liaison Avion Missile, la validation des principes de commandes et visualisations associées .

Ce dernier D.E. mené en coopération entre Dassault Aviation, Thomson CSF et Matra BAe Dynamics s'appuyait sur des simulations pilotées avant de déboucher sur une démonstration des principes retenus, en vol, sur un avion Falcon 20 spécialement modifié.

Déjà l'équipe intégration de Matra BAe Dynamics était sollicitée pour participer à ces D.E.

2.4. Les ingrédients

Tous ces travaux devaient déboucher sur les développements suivants :

- un nouveau concept de cabine par Dassault Aviation, qui sera appliqué sur le 2000-5 puis sur Rafale,
- un nouveau concept radar par Thomson-CSF qui donnera le RDY,
- le missile MICA par Matra BAe Dynamics
- les équipements d'interface associés (Lance-Missiles rail et éjection, boîtiers d'interface, émetteur de la LAM) par Matra BAe Dynamics également

L'avion retenu pour les tirs de développement du MICA fut un Mirage 2000 C, en service dans les forces, dont l'avionique fut modifiée pour donner un "system d'essais" très éloigné d'un système opérationnel mais bien adapté au développement du missile.

Son aérodynamique , en revanche , étant la même , une partie du travail d'adaptation débutait dès cette époque.

C'est en 92 que débutait l'adaptation du MICA au 2000-5.

3- LE PROGRAMME D'INTÉGRATION

3.1. Position du problème

L'intégration est classiquement abordée selon 2 angles complémentaires qui sont

- l'aéromécanique qui traite des questions liées à l'emport et à la séparation,
- l'avionique système qui traite des échanges d'informations entre le pilote et son avion d'une part , l'avion et le missile d'autre part.

Elle se concrétise par le développement d'équipements spécifiques comme les lance-missiles et les boîtiers d'interface, et de fonctions spécifiques à la conduite de tir, mais implantées dans des calculateurs non spécifiques. Les calculs de domaine de tir, ou de temps de vol des missiles, sont des exemples de telles fonctions.

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

Nous allons examiner dans ces différents domaines les tâches du missilier, en suivant l'exemple du 2000-5 / MICA.

3.2. Aéromécanique

La tâche du missilier est de vérifier que le missile supporte les environnements avions.

3.2.1. Emports : la méthode consiste

- à créer une "base de données" d'environnement mécanique, thermique, électromagnétique, soit théoriquement soit grâce aux essais d'intégration (vols d'ouverture de domaine d'emport, essais en chambre anéchoïde,...)
- déduire de celle-ci et du profil de vie du missile les niveaux de qualification souhaitables
- vérifier que les niveaux auxquels le missile a été qualifié couvrent ce besoin,
- éventuellement réaliser des compléments de qualification.

Comme le développement du MICA utilisait un Mirage 2000 en service modifié au niveau du système seulement, les aspects emports ont été explorés avant l' adaptation au Mirage 2000-5, pour les configurations qui étaient utiles au programme des vols de développement. C'est ainsi qu'une partie des configurations retenues pour le Mirage 2000-5 avaient été couvertes.

Seuls des compléments ont été nécessaires au début du Programme d'Intégration.

A l'issue de ces travaux on a pu conclure que la qualification du missile couvrait les besoins de l'adaptation au Mirage 2000-5.

3.2.2. Séparation

Il faut également démontrer l'aptitude du missile à se séparer de l'avion, en toute sécurité, et à réussir sa mission à l'issue de cette phase de séparation.

Traditionnellement, le domaine de séparation était ouvert par des tirs préparés par des essais en soufflerie. Cette méthode comporte plusieurs limites :

- coûts élevés (consommation de matériel) (plus de 100 tirs pour adapter le missile Matra BAe Dynamics R530 à l'avion Mirage III),
- non exhaustivité du comportement : chaque situation vue en vol n'est qu'un cas particulier d'une famille dispersée,
- risques élevés à effectuer des tirs en limite de domaine ou alors approche pas à pas augmentant encore le nombre de tirs,
- soufflerie non valide dans certains domaines (transsonique), imposant une approche purement expérimentale.

Ces limites ont pu être repoussées par l'utilisation de simulations numériques, recalées par l'expérimentation.
Ainsi on a construit un ensemble cohérent d'outils de simulations, régulièrement confrontés à la réalité des essais, et qui constitue le moyen de démontrer les performances attendues.

L'ensemble comprend (cf figure 1)

- une base de données aérodynamique qui caractérise l'influence du champ aérodynamique de l'avion sur le missile en tout point de ce champ avion, cette base de données a pour origine les mesures de soufflerie lorsqu'elles sont disponibles, et les calculs de "soufflerie numérique", obtenus par les méthodes d'Euler ou Chimère, en fonction des besoins.
- le modèle complet du missile, construit tout au long du développement de celui-ci et validé par lui,
- une modélisation complète du lance-missiles et de ses interactions avec le missile, qui fournit les conditions initiales de vol du missile en fin d'éjection.

L'énergie du lance-missile est fournie par une bouteille de gaz haute pression (400 à 500 bars typiquement) dont la distribution vers les vérins d'extraction puis d'éjection est assurée par une vanne à commande pyrotechnique.

La simulation comporte donc :

- un module de calcul de l'écoulement du gaz dans le circuit d'extraction.
- un module de calcul de l'écoulement du gaz dans la partie pneumatique du système d'éjection.
- un module de calcul dynamique des efforts et contraintes dans l'ensemble (LM + missile).

Cette modélisation s'est construite pendant le développement du Lance-Missiles, chacune de ses briques étant validée par des essais particuliers. Elle a servi à préparer les tirs de séparation, et à optimiser la définition série du Lance-Missiles.

Elle a été modifiée, complétée chaque fois que les essais ont montré que les phénomènes physiques étaient mal ou pas représentés.

Plus de 150 tirs au portique, couvrant le domaine de température et d'efforts prévus en vol, ont permis de régler les modèles Lance-Missiles, et le Lance-Missiles lui même,. Plusieurs campagnes de soufflerie ont été nécessaires pour établir la base donnée Aéro, que l'on a complété par des calculs dans le transsonique, et moins de **17 tirs** en vol **dont 11 "sondes aérodynamiques"** (maquettes inertes) ont suffit pour valider l'ensemble (il en avait fallu 100 pour adapter le missile R530 sous le Mirage III).

On a pu ensuite, en faisant tourner la simulation partout dans le domaine visé, démontrer que la séparation, hors cas de panne, se passe toujours de telle sorte que le missile se contrôle sans danger pour l'avion et sans inconvénient pour sa trajectoire future.

Comme le temps disponible ne permet pas de traiter tous les cas possibles, on utilise des méthodes de Monté Carlo pour couvrir, avec un choix approprié de dispersions, l'ensemble des cas possibles.

En parallèle, des études de sécurité menées conjointement par Matra BAe Dynamics pour les aspects Missile et Lance-Missiles et par Dassault pour les aspects avion ont permis de démontrer que le niveau de sécurité spécifié, en emport comme en tir était atteint. Ces études, conduites assez tôt dans le déroulement du programme, ont permis d'identifier quelques point durs et de trouver les solutions ramenant les probabilités de pannes à un niveau acceptable, compatible de l'objectif visé.

Une des conclusions de l'étude a été de conditionner, dans le missile, la mise à feu du propulseur, au respect de critères de position et attitudes par rapport à l' avion

Le modèle de simulation inclus le logiciel du missile, et teste donc ces critères avant d'autoriser la mise à feu du propulseur en simulation.

3.2.3. Importance du choix du lance-missiles

On notera que Matra BAe Dynamics a toujours développé les équipements d'interface liés à ses missiles(Lance-Missiles , Boîtier électroniques,...), avec le souci :

- de mettre dans le Lance-Missiles ou le boîtier tout ce qui n'est pas nécessaire au vol libre du missile

par exemple	Alimentation basse tension Séquencement de l'allumage des dispositifs electropyrotechniques certaines surveillance liés à la sécurité de l'avion

- d'optimiser le couple, vis à vis des contraintes imposées par l'avion d'une part et des performances demandées au missile d'autre part . On a pu ainsi relâcher la contrainte sur la vitesse verticale minimale en fin d'éjection demandée par le missile, sans toucher aux performances finales.

Ceci conduit globalement à un missile plus léger et plus compact (30 % de masse, et 40 % de volume en moins que l'AMRAAM) dont le coût de possession est réduit puisque moins de consommables ,tout en ayant des performances équivalentes à celles de l'AMRAAM dans le domaine de ce dernier, et des capacités au combat tournoyant uniques.

On mesure ici le bénéfice retiré de cette situation au moment de l'adaptation, puisque le modèle éjection mèle intimement LM et missile. On a ainsi gagné un temps précieux dans la résolution des problèmes de contrôle du missile pendant l'éjection, grâce à une boucle étude → essais → modification particulièrement rapide et efficace.

3.3. L'avionique système

3.3.1. Le processus

A côté des aspects aéromécaniques, le missilier est également partie prenante dans l'élaboration de l'avionique système.

La nature multi-tâches / multi équipement de celle-ci impose la méthodologie dite du développement en V.

La première étape de la descente du V est la phase de "Définition globale". Elle consiste à élaborer des chaînes fonctionnelles qui optimisent :

- d'une part la nature, la précision, l'age de données avions fournis au missile
- d'autre part l'utilisation du système par le pilote.

Les outils privilégiés dans cette phase sont des simulations :

- simulations numériques pour la définition de l'interface missile
- simulations pilotées pour l'Interface Homme Machine (I.H.M.)

Les contraintes à respecter sont les caractéristiques des équipements avions non spécifiques à la fonction (capteurs, Visualisations...), les ressources allouées dans l'ensemble des calculateurs (charge de calcul, taille mémoire, charge bus,...) et le niveau de sécurité demandé.

La deuxième étape est la définition détaillée c'est à dire la spécification matérielle et logicielle de chaque équipement de la Conduite de Tir compte tenu des choix faits à la première étape.
Les équipements occupent la base du V leur réalisation en finit la descente,leur qualification aux environnements avion et la vérification de leur conformité aux spécifications en débute la remontée.

La remontée du V se poursuit par une première batterie de validations fonctionnelles, qui s'effectuent chacune pour un groupe d'équipements réalisant une chaîne fonctionnelle donnée.

Un banc dit "Banc de Prévalidation" permet par exemple d'effectuer chez Matra BAe Dynamics la validation de l'ensemble constitué par les équipements en interface avec le missile (Lance-Missiles, boîtiers d'interface, émetteur LAM...) en simulant le contexte système de ce groupe d'équipements de façon représentative, en particulier au niveau de la dynamique des échanges de données. L'ensemble livré au banc d'intégration avionique de l'avionneur est cohérent, et conforme aux spécifications d'interfaces avec l'avion.

Le couronnement de la "remontée du V" consiste en la validation complète de la Conduite de Tir qui se fait, tant pour l'interface missile que pour l'IHM, au banc avionique de Dassault Aviation, puis sur l'avion par des essais sol et vol.

3.3.2. Le modèle de performance du système

Tout au long de ce processus on a construit, élément par élément, la simulation globale que les essais ont validé étape par étape. (cf figure 2)

Dans ce domaine, chaque industriel entend préserver son savoir faire, vis à vis de ses éventuels concurrents, en ne fournissant à ceux-ci, éventuellement, que des modèles adaptés, dits "de comportement". Ceux-ci sont représentatifs, mais pour les fonctions utiles à l'étude uniquement.

Les modèles complets, analytiques, ne peuvent être fournis qu'à une autorité indépendante.

Ceci conduira à ne disposer d'un modèle complet et fin que dans un centre étatique, pendant la phase de remontée du V.

Dans la 1ère étape :

la simulation utilisée est triple : chaque industriel dispose des modèles adaptés fournis par les autres, et de son propre modèle complet.

Ceci a permis à chacun d'étudier chacune des chaînes fonctionnelles, avec le maximum de finesse sur sa partie et suffisamment sur le reste, pour juger des influences.

Matra BAe Dynamics a donc fourni à Dassault Aviation et à Thomson-CSF un modèle MICA adapté.

Matra BAe Dynamics a pu ainsi, à partir des modèles de comportement du radar et de l'avion , vérifier les choix de conception des chaînes, la sensibilité des performances du missile aux données d'entrée, et ainsi maintenir les demandes critiques tout en relâchant les contraintes sur les données moins sensibles.

Dans la phase finale de remontée en V, les essais au banc avionique et les vols portés fonctionnels ont complété la validation du modèle.

Celui-ci a ensuite été utilisé pour préparer les "tirs de qualification système", en permettant de choisir tous les paramètres du tir en vue de démontrer le maximum de fonctions.

Il a produit des prévisions, pour le déroulement de l'essai, sur l'ensemble des performances démontrables.

Chaque tir d'essai a servi à vérifier que la simulation était correcte, à la recaler si nécessaire si bien qu'à l'issue de tout ce travail la simulation a été déclarée conforme au système.

Des centaines d'heures d'essais au banc quelques dizaines d'heures de vol et 5 tirs ont servi spécifiquement à cette validation.

On bénéficie ainsi d'une simulation complète et validée, à la disposition de l'utilisateur, qui a permis de démontrer les engagements des industriels, mais qui peu servir à explorer d'autres situations pour évaluer le système au delà des engagements pris.

4. CONCLUSION

L'adaptation du MICA au 2000-5 a représenté un programme en soi dans la continuité des programmes missile, radar et avion qui la rendaient possible.

Dans ce programme, le missilier a été intégré très tôt auprès du radariste et de l'avionneur, car les choix d'architecture s'appuyaient sur des simulations dont celle du missile. Ces simulations ont été enrichies tout au long du programme, confrontées aux résultats d'essais, modifiées en conséquence, pour constituer en finale l'outil de démonstration des performances

Enfin ce programme a montré que confier le développement des équipements d'interface au missilier,.choix de longue date qui avait permis d'optimiser le missile pour son vol libre, a facilité la résolution des difficultés nouvelles posées par l'éjection.

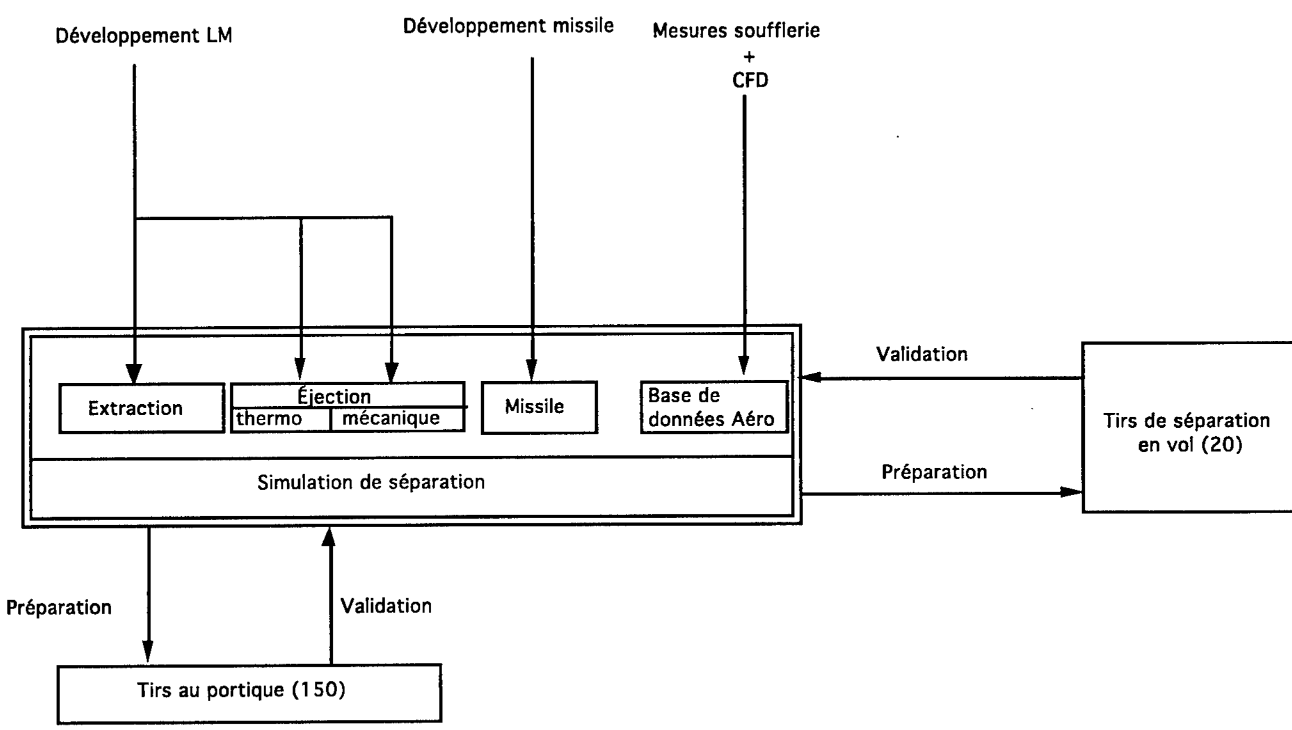

Figure 1 : Le modèle de séparation

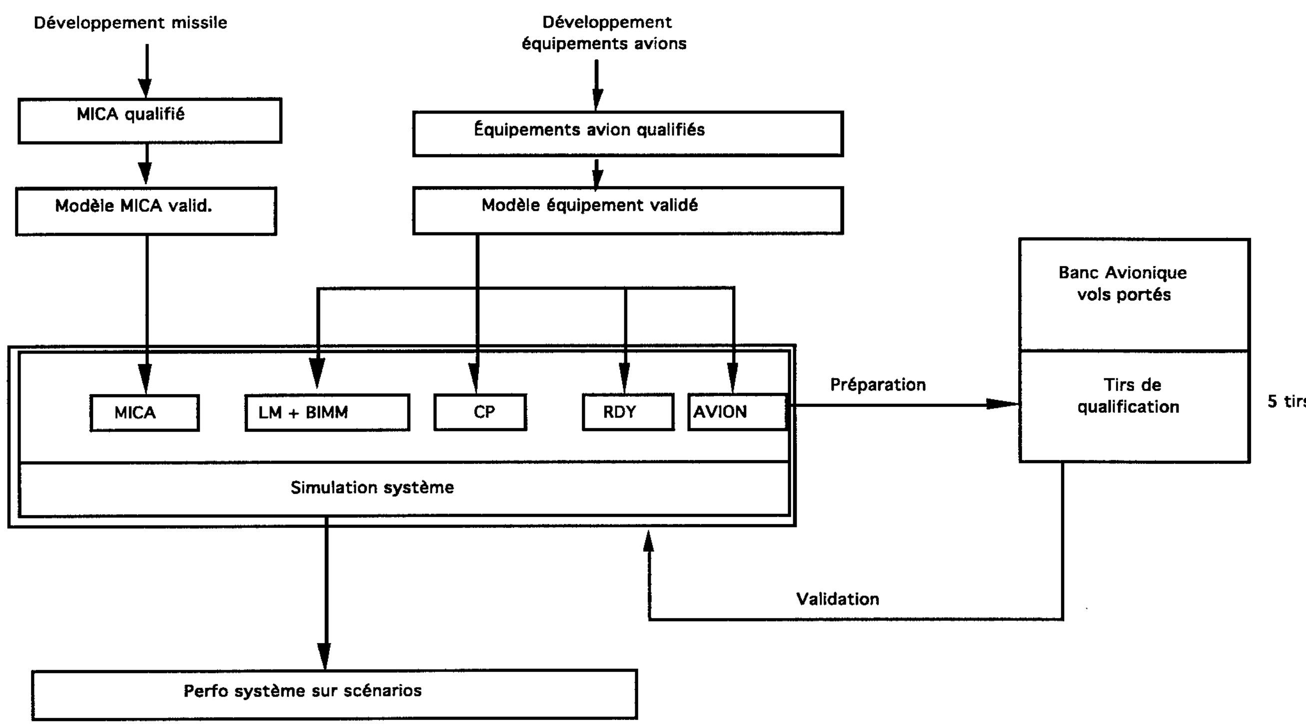

Figure 2 : Le modèle de performances du système

AIR-TO-GROUND WEAPON AIMING
A BRIEF SYNOPSIS TO DATE AND A LOOK TO THE FUTURE

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1 SUMMARY

A review of air-to-ground weapon aiming is given, with emphasis placed on the use of the Head-Up Display (HUD), the main cockpit instrument used for accurate weapon aiming over the last 35 years. Nevertheless, the HUD is only of use for the aiming of forward-firing weapons. More advanced weapons have an off-axis capability and their aiming is greatly facilitated by the use of a Helmet-Mounted Sight (HMS) or Helmet-Mounted Display (HMD). The surface-to-air threat and the rules of engagement, particularly in operations other than war, place high demands on the aircrew and the weapon aiming system, both to stand off from the target and to have a high degree of confidence that it *is* the target. The requirement to perform an accurate in-flight transfer alignment of the weapon places further demands upon the aircrew. Timely and accurate target data, digitally received, plus an on-board targeting system which can automatically search for and recognise a target, are of great utility in the final stages prior to weapon release. The Defence Evaluation and Research Agency is performing research in these areas.

2 INTRODUCTION

Air-to-ground weapons were first released from balloons. Since the beginning of World War 1 (WWI) heavier-than-air craft have been similarly employed, flying faster and aiming and releasing their weapons more accurately. Whereas in the early days the weapon and its means of aiming were literally a bolt-on or carry-on extra, a modern military aircraft is more typically described as a weapon system, a considerable proportion of the cost of which is associated with the avionic systems which contribute directly or indirectly to the aiming and release of the weapons.

As the world adjusted to the shock of using aircraft to release weapons, so ground defences against this threat evolved from the speculative aiming of hand-held guns and rifles through radar-directed, powerful anti-aircraft fire and finally to the employment of fixed, mobile and man-portable surface-to-air missiles.

As ground defences evolved, so too did the means of airborne weapon aiming. The rudimentary aiming devices of WWI became the more complex and accurate gunsights in WWII fighter aircraft and sophisticated bomb-sights such as those employed on the large US bombers. The advent and maturation of the jet engine meant that the weapon load of a 10 crew WWII bomber could be carried by a single crew 1970's fighter/bomber. The ability then to release air-to-ground weapons in the dive assured the ongoing requirement for the use of the HUD. First in service in the Buccaneer in 1961, the HUD has developed from offering an instantaneous field of view of approximately 15 degrees circular to almost 30 x 25 degrees on the Eurofighter. Comparable, and generally better, improvements have been made in brightness, accuracy and reliability. Greater computing power enabled the calculation and display of symbology to support the use of the HUD aiming reticle not only in wings-level aiming but also at very high bank angles, thus significantly increasing flexibility of approach to target at the final stage of the attack.

Proliferation of the availability of all types of surface-to-air missiles has dictated the requirement to be able to stand off some kilometres from the target, militating against the use of ballistic weapons. Stringent rules of engagement, particularly in operations other than war, often require positive target identification by the attacking aircraft prior to marking the target. The constraints of having to stand off from the target and yet still positively identify it have led to research into the third party provision of digital target data directly into the cockpit, the use of helmet-mounted devices for off-axis designation, and the automation of target search, acquisition and identification.

3 EARLY WEAPON AIMING FROM HEAVIER-THAN-AIR MACHINES

The utility of aircraft for the release of air-to-ground weapons was not immediately obvious to all in the early years of flight. Indeed, in 1911 Major Brooke-Popham of the Air Battalion of the Royal Engineers was rebuked by his superiors for fitting a gun on to his Blériot monoplane. Early WWI aircraft were unarmed and in 1914 the aeroplane was still regarded with misgivings by the British War Office on the ground that it "would frighten the horses" (Ref 1).

Nevertheless, early pilots were well aware of the military potential of their craft, and in September 1914 a French Bréguet scout plane had dangerous holes made in its wings when a German pilot threw a brick down on it. The French, on their part, carried slingshots and steel darts called flechettes. Also, the hand grenade came into use, some of which were dragged behind the aircraft on cables in the hope of entangling them in the enemies'

Paper presented at the RTO SCI Symposium on "Aircraft Weapon System Compatibility and Integration", held in Chester, United Kingdom, 28-30 September 1998, and published in RTO MP-16.

propellers. Pistols, carbines, shotguns and even grapnels on the end of ropes were used (Ref 2). By 1914 the USA had flight proven the feasibility of firing on ground targets with an aircraft machine gun and had improved a bombsight to a successfully useable level (Ref 3). The first airborne bombing of a capital city was on the outskirts of Paris when one Oberleutenant Dressler dropped some 4-pound bombs from a Taube flier: no damage was done. The first WWI aircraft brought down by ground fire was that of Leutnant Reinhold Jahnhow on August 12, 1914, by French infantry. A little later Seargeant Major D S Jilling was wounded by German ground fire (Ref 4).

The first organised use of the aeroplane as an offensive weapon was the autumn of 1914 when the *Aviation Militaire* began to assemble a force of mostly Voisin-equipped bombers. By May 1915 the Royal Flying Corps had 2260 aircraft on order. Raymond Saulnier temporarily solved the forward-firing gun problem not by synchronisation (since some of the cartridges of the Hotchkiss gun had 'hung fire' and caused trouble) but by steel deflector plates on the propeller of the Morane-Saulnier monoplane. However, in April 1915, Roland Garros was unable to destroy the Morane in which he force-landed behind German lines, and in that July the first of the Dutchman Anthony Fokker's E monoplanes were in action with forward-firing guns using an interrupter gear (Ref 1).

4 months later a lost German Fokker landed in thick fog at a French airfield and was captured. However, the French ignored the deadly effective gun invention, and the British, finding that the Germans held all Fokker's patents, refused to copy the invention, and for some time to come the Allied pilots suffered the terrible consequences (Ref 4).

2nd/Lt R.B. Bourdillon, having evolved a simple but effective bomb sight using nails and wire, was sent to the Central Flying School, Upavon, in December 1914. There he devised the C.F.S. bomb-sight, which was in service for 3 years. The pilot used a stopwatch to time the difference between 2 sights taken on one object. He then obtained the correct angle for bomb dropping by setting the movable foresight on a timing scale to the measured observation interval. The final 18 months of the war saw the introduction of the High Altitude Drift Sight Mk Ia, which allowed for height, airspeed and wind; the Mk II, which was similar but included automatic levelling; and the Negative Lens Sight, which simply comprised one or 2 lenses mounted in the floor of some cockpits. The Germans began their bomb-sight work with the optical firm of Zeiss before the war began, resulting in an improved version in 1916 which, similar to the British sight, also required observer stopwatch measurement of one landmark through 2 different parts of the sight (Ref 5).

4 THE GYROSCOPIC SIGHT

Improvements in aircraft armament, speed and manoeuvrability caused the requirement for an improved weapon aiming capability, particularly for air-to-air engagements. In 1938 the most promising solution appeared to be the Royal Aircraft Establishment's (RAE) suggested use of the gyroscope to ascertain relative target motion and thence lead angle. The first technical note in the RAE's current archives is from 1939, concerning the theory of the gyroscopic gunsight. Design and development of the equipment reached sufficient maturity in the Mk IIC turret sight by the end of 1941. Successful embodiment in 1942 led to the slightly modified Mk IID sight for fighters in 1943, which improved the chances of combat success to 50% from the previous, normal 20%. Further simple modification led to its use for air-to-ground rocketry by accommodating wind, target motion and weapon gravity drop. Lack of US acceptance of the gyro sight changed through the war (Ref 6). In 1943 two US pilots evaluated the Mk II gyro gunsight against the GM2 fixed sight, both flown in a Spitfire VB against a Spitfire target at up to 380 mph and up to 4.5 degrees lead angle. Both evaluation pilots were combat experienced. Lt Col C G Peterson, of the 4th Fighter Group, 8th Fighter Command had 8 enemy aircraft destroyed and 7 probably destroyed. His (at that time secret) evaluation report concluded: "I believe this sight would improve gunnery at least 100%. Shooting for the moment is, for most pilots, pure guess work. A pilot cannot guess with this sight and due to this I am sure that at least the lower bracket of pilots (75%) will improve their shooting to the level of the best gunnery shots now, and the best ones can do even better. It is easy to handle and there is no situation that it cannot handle as well as the GM2 and most cases (90%) it will do a hell of a lot better. Buy me one."(Ref 7) By the middle of 1944 the USA was producing more of the British type of gyro sights than were the British (Ref 6). RAE archived technical notes on the subject continue to 1957, through correction for aircraft incidence (1952), 3-gyro gunsight for 2.75" rockets (FFAR) (1952), range calculation (1953) and accommodation of sideslip (1953).

5 THE HEAD-UP DISPLAY

HUD development followed from the gyro gunsight, with the first production HUD being in the Blackburn Buccaneer in 1961. The equipment has now reached such maturity, and its utility is so accepted, that not only do all modern aircraft designs, such as the Eurofighter and the F-22, include a HUD, but many older aircraft, such as the F-5, MiG-21 and F-104 have been retrofitted with a HUD.

A very strong point in favour of the use of the HUD for weapon aiming is that if the avionic data supplied to the weapon aiming calculations are within specification, then the accuracy of the weapon is statistically deterministic. Put simply, the weapon will land within a HUD-drawn circle, or ground ellipse, around the target, much as when aiming and firing a rifle. (The wide experience of the main author with squadron aircraft across the world is that various avionic equipments are frequently not within specification of calibration, alignment etc., and weapons initially fall outside of an

acceptable Circle of Equal Probability (CEP)). A typical parametric error type of calculation for a HUD-based weapon release is shown in table 1.

is possible that the distance between successive impact points is larger than the expected aiming error, and significantly larger than the target. Such was the case when the RAF cratered the Port Stanley runway from high altitude during the Falklands conflict.

Error Source	Magnitude (1σ)	Along Track		Across Track	
		Sensitivity	Error (m)	Sensitivity	Error (m)
INS elevation	2.0 mr	2.06	4.1		
INS azimuth	2.0 mr			0.6	1.2
Vz	0.3 m/s	8.6	2.6		
Groundspeed	0.9 m/s	4.0	3.7	4.0	3.7
Height	2.5%	2.0	10.3		
Terrain slope	6.1 m	6.7	41.1		
Airspeed	2.3 m/s	-1.4	-3.2		
Wind	0.4 m/s	1.4	0.5	1.4	0.5
Ballistic Comp	3.0 m	1.0	3.0		
Sideslip	4.5 mr			0.3	1.4
Pilot Aiming Al	3.0 mr	6.2	18.5	0.6	1.8
HUD harmonisation	0.5 mr	6.2	3.1	0.6	0.3
HUD distortion	1.0 mr	6.2	6.2	0.6	0.6
Windscreen distortion	1.0 mr	6.2	6.2	0.6	0.6
Release delay	0.02 s	232	4.6		
Ejection velocity	0.3 m/s	8.6	2.6	2.6	0.8
Release disturbance	0.6 m/s	8.6	5.2	2.6	1.6
Weapon retard	0.04 s	52.8	2.1		
Total RSS			48.4		5.0
CEP (m) = 0.6 x RSS (along) + 0.56 x RSS (across) = 32 m					

Table 1: Example of a parametric error assessment for a through-the-HUD retarded weapon release

The example given in the table is for a 450 kt retarded bomb laydown at 200 ft using a radar altimeter over sloping ground, aimed through the HUD. The example indicates well the number of parameters to be considered in assessing the total accuracy of a HUD-aimed weapon, the positive side of this being that all the parameters are measurable. This particular release geometry, with a high drag bomb, is susceptible to a large along-track error. A slick bomb released in a medium angle dive is equally deterministic and far more accurate. An example of the accuracy which may be obtained when aiming with a HUD is given by the biennial USA Gunsmoke air-to-ground competition. This was won in 1985, with bombs released in 200 ft level flight, by an F-16 flown by Col Lyle of 419TFW, Hill AFB, Utah. The second aircraft, also an F-16, was flown by Capt Fredenburgh of 50TFW, Hahn AFB, Germany. The winning and second aircraft had a Circular Error Average of 0.25m and 1.75m respectively (Ref 8). Of course, inaccuracies in weapon delivery can be offset to some extent by the release of multiple weapons, thus increasing the area of effect beyond the expected individual error. However, this necessarily reduces the number of targets that a given aircraft can attack, and can be counter to the mission objective when there may be a specific requirement to minimise collateral damage. Other problems can arise from the physical constraints imposed by the need for safe separation. In the case of ballistic weapons a multiple release can make weapon aiming very difficult. The minimum time allowed between successive releases can correspond to a large distance on the ground when an aircraft is travelling at high speed. It

Until the 1980s the HUD displayed a straight bomb fall line, drawn vertically in earth axes, which assisted the pilot in executing a wings-level attack by placing the bomb fall line through the target and tracking the target down the line until it was coincident with the Continuously Computed Impact Point (CCIP), at which time the weapon would be released. The continuous computation and updating of the impact point afforded considerably more flexibility than the Vietnam era use of the gunsight, the depression of which had to be preset for a release at a calculated height, dive angle and airspeed. In order to aim accurately, the gunsight-equipped aircraft was obliged to fly wings level at a pre-chosen airspeed and dive angle until a specific height above target. The requirement to fly a predictable trajectory caused the loss of many aircraft to ground fire. The HUD removed the requirement for a 'canned' height, speed and dive angle but still required wings level aiming for an accurate release, with the associated predictability of aircraft track and therefore exposure to predicted ground fire. Greater computing power enabled the calculation and display of symbology to support the use of the HUD aiming reticle not only in wings-level aiming but also at very high bank angles, thus significantly increasing flexibility of approach to target at the final stage of the attack. This was achieved with a HUD line replacing the straight bomb fall line, emanating from the CCIP marker, and which indicated the predicted plot of the CCIP over the ground during banked flight. The CCIP calculation itself

was unchanged, but the pilot could now aim accurately at high bank angles using the same principle of tracking the bomb fall line, now curved, through the target, until target and CCIP marker were coincident. Equally deterministic accuracy was then available at high bank angles.

The following figures 1a - 1d are chronologically sequential and depict the high utility of the predicted bomb impact line. The symbology indicates a 5 degree dive at 360 kt in a 45 degree left bank. Accurate aiming with a straight bomb fall line drawn vertically in earth axes would be virtually impossible, particularly in a hostile environment. These figures, however, show that if the aircraft is rolled until the predicted bomb impact line overlays the target, initially in the top left quadrant (figure 1a), and the bank angle is maintained, the target will track down the line (figures 1b and 1c) until coincident with the computed impact point (figure 1d). Experience shows the symbology to facilitate final stage aiming refinement. For example, in this display, if the curved line were initially above the target the pilot would simply roll progressively further left until target/line coincidence was achieved.

The HUD offers high utility when aiming many forward-firing weapons, particularly those travelling ballistically and with relatively short forward throws, namely bombs, bullets and rockets. However, the use of such weapons, particularly for the attack of high value targets, requires greater penetration than is desirable when considering the availability and ubiquity of surface-to-air missiles (SAMs). More modern weapons travel further (e.g. Paveway III) and have an off-axis capability (e.g. Brimstone and JDAM). Exploitation of the off-axis capability is an important area of research.

Figure 1a

Figure 1b

Figure 1c

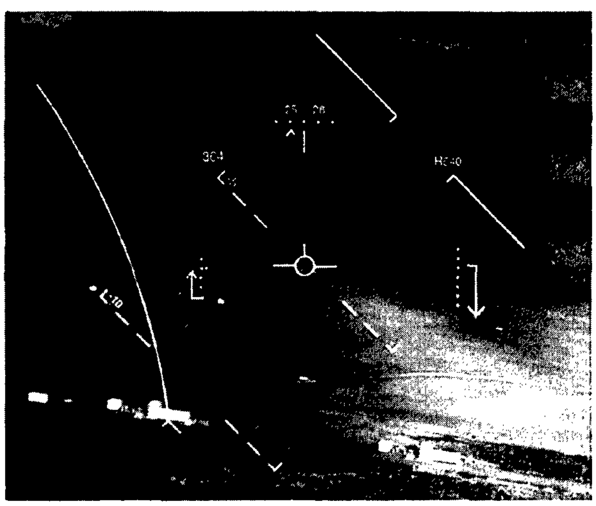

Figure 1d

Figure 1: Sequential indication of HUD weapon aiming with a curved bomb impact line

6 OFF-AXIS AIR-TO-GROUND WEAPONS

Up to the present time the delivery of air-to-surface ordnance has generally been carried out in the direction of travel of the delivery aircraft. The reasons for this are simple: firstly, bombs are unpowered and are reliant on the velocity of the releasing aircraft for their own kinetic energy, so with no guidance they follow a ballistic trajectory; secondly, rockets and bullets have an additional velocity but to aim them off boresight would require unacceptably cumbersome and heavy mechanics. With the advent of self-propelled and guided munitions the scope for greater manoeuvre becomes available. However, limitations in the aiming method has again restricted the line-of-flight of weapons to a narrow forward cone. The aiming of such weapons is performed using symbology drawn on the Head Up Display which may offer only ± 10° field-of-view from the aircraft heading. Additionally, the dynamics of the air-to-ground engagement are much lower than the air-to-air case (aircraft do not get into turning fights with tanks very often) and so the requirement for off-boresight delivery is not so acute.

The advent of the helmet mounted display now offers the pilot the possibility of designating a target well away from the aircraft axis. This capability is finding its way rapidly into the air-to-air arena; aiming the UK advanced short range air-to-air missile (ASRAAM) is via helmet-mounted sight where the IR sensor is slaved to the helmet. This gives the potential for aiming and launching the weapon at up to 90° off-axis. The US XAIM-95 programme demonstrated a 55g 118° angle-off attack launch prior to the programme's termination (Ref 9).

In the air-to-ground theatre similar weapons are not yet being fielded in great numbers. However the potential for 'over-the-shoulder' delivery of air-to-surface weapons is growing. The new Advanced Anti-Armour Weapon - Brimstone - under procurement for the UK is an example. Visual designation may be performed by overlaying an aiming patch displayed on the HUD over the target area, as shown in figure 2.

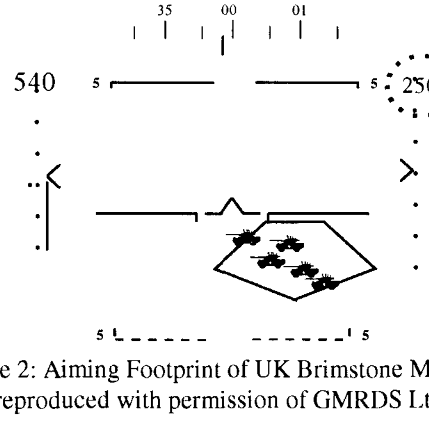

Figure 2: Aiming Footprint of UK Brimstone Missile (reproduced with permission of GMRDS Ltd)

The aiming 'footprint' can be slewed left or right within the field-of-view of the HUD, offering some degree of off-boresight capability. The potential of such a system aimed in conjunction with a helmet-mounted display would be high, enabling a pilot to engage targets at high angles off-boresight, thus negating the need to approach directly. The Brimstone system offers the potential for off-axis aiming of up to 40 degrees, giving the pilot latitude for manoeuvre across the battlefield while still being able to engage late-show targets off aircraft heading. Target search, acquisition and designation as early as possible, and also off axis, is beneficial, and necessary in order to utilise the maximum potential of the weapon. DERA research has shown the utility of the HMS and HMD for these purposes.

7 GROUND SYSTEMS IN AREAS OF CURRENT NATO OPERATION

The range of land-based air-defence systems now deployed world-wide is vast and a thorough review would be well outside the scope of this paper. Therefore a brief summary will be made of the systems being encountered by NATO forces in 2 current deployments. These are Operation SOUTHERN WATCH, the enforcement of the 'no-fly' zone over southern Iraq, and Operation DENY FLIGHT in the former Yugoslavia. The capabilities of the ground systems will be examined along with their consequences for the way operations are carried out by coalition aircraft. Performance figures quoted are from Ref 10.

IRAQ

The primary fixed-site SAMs deployed by Iraq are the SA-2 and SA-3, both of Former Soviet Union (FSU) origin. The SA-2 is an ageing system but still effective up to an altitude of 30000m using command guidance. SA-3 has a maximum altitude of 18000m and also uses command guidance. In order to effect an intercept, therefore, the target must be continually tracked, which for the SA-2 is performed by a standard con-scan technique ('Fansong' radar). The SA-3 uses track while scan (TWS) via 2 orthogonal parabolic aerials (the 'Low Blow' radar). Variants of SA-3 can also track targets via TV, and an IR homing seeker is understood to have been developed by the Iraqis. The primary self-defence technique for defeating these systems would be that of plain-noise jamming to deny range or angle-stealing the tracking radar using amplitude-modulated noise.

Iraq also deploys a number of self-propelled SAM systems notably the SA-6 (using semi-active homing), the SA-8 and Roland 2 (both command guidance) and SA-9 and -13 (both IR homing). The maximum effective altitudes of these systems are between 6000m (IR) and 15000m (radar). A large stockpile of Man Portable Air Defence Systems (MANPADS) is held; SA-7, -14 and -16 all of which rely on IR guidance. A maximum altitude of 6000m is typical but the kill probability (P_k) of such systems is typically very low.

A range of calibre of anti-aircraft artillery (AAA) is held, including 14.5mm ZPU, 23mm ZSU, 57mm S-60, 85mm KS-12 and 100mm KS-19 and KS-30. AAA is seldom effective above 6000m, but below can pose a major hazard through sheer volume of fire even without guidance.

FORMER YUGOSLAVIA

Following the break-up of the former Yugoslavia a variety of equipments have come into the hands of various factions. The systems encountered are mostly FSU systems and are believed to include some SA-10. Again, an extensive range of AAA systems is available, including most calibres available to FSU forces.

The only fixed-site system present is the SA-3 with performance essentially as quoted above. SA-6 (as shot down Capt Scott O'Grady's F-16 in 1996) and SA-9 are also known to be fielded. The SA-11 is a development of the SA-6 system introduced by the FSU as a replacement for the SA-4. With an effective maximum altitude of 22000m the SA-11 has also demonstrated capability against low-flying helicopters. Using semi-active homing for guidance the SA-11 also fields a number of sophisticated electronic counter-countermeasure (ECCM) techniques.

1-2 batteries of the S-300P version of the SA-10 system were delivered and are understood to be still fielded. This highly capable system uses command guidance and is effective between 25m and 30000m with a missile fly-out speed of up to Mach 6 and range up to 160 km. With a variety of sophisticated ECCM techniques the SA-10 is considered to be one of the most potent air-defence systems currently fielded.

8 AIR DOCTRINE

The presence of such systems in an operational theatre poses a number of constraints on those forces carrying out peace-support tasks or, indeed, any other forms of airborne operation. These include choice of force mix, operating altitudes, avoidance of missile engagement zone (MEZ) and Rules of Engagement (ROE). Air Power Doctrine for the UK is described in *AP3000 Air Power Doctrine* (Ref 11) issued by the Royal Air Force and seeks to act as the foundation of the UK contribution to joint-service doctrine and alliance doctrine with NATO or other allies, so that inter-Service and inter-Allied co-operation is strengthened.

One of the major drivers in the employment of air power is the operating height at which offensive support aircraft will fly. Traditionally this has been dictated by the perceived SAM threat and likelihood of radar detection. Thus the need for low-level operations has been emphasised and is a doctrine still applicable where a sophisticated Air Defence Ground Environment exists. Although such a tactic may provide defence against radar-laid systems, it leads aircraft to a greater vulnerability against the more unsophisticated threat of AAA and MANPADs. Indeed, during Operation DESERT STORM the greater threat to aircraft from AAA systems, in the face of a much reduced SAM threat, played a part in leading the RAF to adopt medium level tactics as the air campaign proceeded.

Where the threat from SAM systems is either non-existent, or can be contained or eliminated as required, the option of medium level operations is available. The advantage of this is that it takes patrolling aircraft out of the range of AAA, MANPADS and some radar SAMs such as ROLAND. Where the positions of fixed site SAMs are well known constraints on routeing can be made to avoid the associated missile engagement zone (MEZ). Medium level operations themselves are the preferred option where the day-to-day task is largely a surveillance one and reconnaissance equipments are designed around medium level use.

During peace-support operations the attendant risk of losing aircraft to unsolicited ground-fire must be minimised. This drives the force package to include a high content of SEAD (Suppression of Enemy Air Defence) dedicated platforms - HARM-equipped F-16, EF-111 'Raven' and supporting surveillance platforms such as E-3D and RJ-135. The availability of 'HARM/ALARM-shooters' to cover a reconnaissance flight near, or through, a known MEZ provides a credible self-defence capability ensuring any activation of associated SAM radars will be responded to swiftly.

Whatever the threat, however, the general requirement for all attacking aircraft is becoming one of releasing weapons without the need to over-fly the target - or even approach too closely. This has driven the need for stand-off weapons which incorporate their own autonomous guidance systems; greater release ranges preclude aiming through conventional ballistic solutions. The nature of the threat also drives the method by which a target will be acquired. A 'line-of-sight' sensor, such as the US LANTIRN pod or UK TIALD pod allows a more accurate location and designation of a target. However the target being line-of-sight to the aircraft implies the aircraft is also line-of-sight to the (probably well-defended) target. The risk to the attacking aircraft, therefore, must be taken into account in deciding the viability of attacking that particular target. An alternative, where the target is fixed and so its position known - a bridge mensurated from satellite imagery for example - is to pre-programme a weapon with target details and effect release from some distance outside the known threat envelope.

9 RULES OF ENGAGEMENT (ROE)

The UN Charter and customary international law generally prohibit the threat or use of force except in self-defence. Self-defence includes enforcement actions by the UN, self-defence actions by individuals or groups of nations, collective actions by regional security organisations and self-help interventions by individual nations to protect their nationals. ROE are the primary means by which the national command authorities

provide guidance to forces on the ground concerning the application or constraints on the use of force.

Peacetime ROE are premised on the right of self-defence and, therefore, generally limit the use of force to defensive responses to a hostile act or a demonstration of hostile intent. ROE during war or armed conflict, when enemy forces have been declared to be hostile by national command authorities, are then premised on the law of armed conflict. In wartime, ROE limit the means and methods of warfare by placing restrictions on certain weapons and targets, or by imposing specific restrictions for the protection of friendly forces and of civilians or other non-combatants. Although international law relating to the use of force is an important consideration in the drafting of ROE, other factors, such as political concerns, diplomatic issues and operational capabilities are taken into account. Indeed, these often affect the use of force permitted in military operations far more than considerations of international law (Ref 12).

ROE, then, define the degree and manner in which military force may be applied in any given situation. They ensure that force applied is justified and is the minimum required commensurate with achieving the objective, military or political. This has major ramifications for the way a commander may carry out the targeting process.

A key issue for commanders and planners is in deciding what constitutes a legitimate target and how it may be attacked. This revolves around the principles of distinction and proportionality. Attacks should be limited to combatants and other military objectives. The civilian population and civilian objects must not be deliberately targeted; the morale of an enemy's civilian population is not a legitimate target and attacks designed to spread terror among the civilian population are expressly prohibited (Ref 13). Even military objectives should not be targeted if an attack is likely to cause (collateral) civilian casualties or damage which would be excessive in relation to the direct military advantage which the attack is expected to produce. The law stipulates that the military worth of a target needs to be considered in relation to the circumstances at the time. Therefore, a commander needs to have an up-to-date assessment of the significance of a target and the value of attacking it. If there is a choice of weapons or methods of attack available, a commander should select those which are most likely to avoid, or at least minimise, incidental civilian casualties or damage. However, he is entitled to take into account factors such as his stocks of different weapons and likely future demands, the timeliness of attack and risks to his own forces. Nevertheless, there may be occasions when a commander will have to accept a higher level of risk to his own forces in order to avoid or reduce collateral damage to the enemy's civilian population (Ref 14).

Within the UK, ROE are issued under Ministerial authority and may only be changed with ministerial approval. The standing document of the application of ROE is JSP 398 where a list of over 20 separable ROE are defined, each with a series of progressive measures as escalation is required. Having defined the ROE for any particular situation the constraints on weapon delivery may then be very tight. For example, the use of electro-optical sensors (Forward Looking Infra-Red, FLIR) may not be allowed to be used for weapon delivery since the available resolution of a thermal picture may not be considered sufficient to permit reliable target identification where the target is, say, a small vehicle. The system may, however, be used where the target is a building and positive identification can be assured. Similarly the use of autonomously guided weapons may be disallowed in favour of entirely man-in-the-loop systems.

10 AUTONOMOUS WEAPON GUIDANCE/NAVIGATION

Unlike purely ballistic weapons, autonomous air-to-ground weapons generally require complex navigation and guidance systems. Target information is sent directly to the weapon so that an internal system can be used to control the weapon's trajectory. This information typically includes the expected target position (e.g. latitude and longitude co-ordinates) and possibly target velocity information, but it may also include data useful to a seeker system (e.g. search parameters and expected target types). Weapon navigation systems can incorporate several different subsystems. The basic source of navigation data is an inertial measurement unit (IMU), but this may be augmented by a global positioning system (GPS), a terrain-referenced navigation system, a scene-referenced navigation system, or some combination thereof. Typically, the choice of navigation system is driven by requirements on weapon navigation accuracy, the weapon maximum and minimum ranges and the cost of the navigation unit. Shorter range stand-off weapons with terminal phase seeker systems (see below), such as the Brimstone anti-armour weapon (Ref 15), tend to rely on inertial guidance for the initial fly-out phase. Those with a longer range (e.g. JSOW [Ref 15]) or without a seeker system (e.g. JDAM [Ref 16]) often use GPS information to enhance the accuracy of their navigation/guidance system. Cost becomes an issue because a weapon navigation system is not generally reusable and must therefore be expendable. Consequently, weapon navigation systems tend to be of much lower quality than those installed in aircraft.

In order to navigate accurately from the delivery aircraft to the expected target position, the navigation system needs to be initialised with data regarding its current position and orientation/attitude. At its simplest level this alignment procedure requires the provision of a 'snapshot' of the aircraft navigation data to the weapon. However, the use of more sophisticated alignment procedures, involving the transfer of a series of aircraft navigation data to the weapon, can be used to offset some of the deficiencies of a low quality inertial measurement unit. By analysing the time-dependent behaviour of the weapon IMU, and comparing it to the data obtained from the aircraft systems, it is possible to

estimate some of the errors present in the weapon navigation system (e.g. drift errors and bias errors) and to correct for them in the navigation algorithms. This transfer alignment process can be an important part of weapon aiming, since it can considerably reduce the overall error associated with placing a weapon on a target. However, the use of such techniques should not adversely affect other factors. There are requirements that the alignment process is done quickly, accurately and robustly. The need for a long alignment process may reduce the flexibility of a weapon system, by limiting its responsiveness. In addition, the need for complex algorithms will tend to increase the computational load on the weapon processors, and the exchange of data between aircraft and weapon could put an additional requirement on the provision of navigation data via the aircraft data bus.

11 CREDIBILITY OF TARGET DATA

The accuracy with which an autonomous weapon may be deployed against a given target is dependent on many factors. The weapon navigation system is provided with an estimate of the target location, which is used to guide the weapon from the aircraft to the expected position of the target. If small navigation errors are present they may be compensated for by using some form of additional terminal phase guidance to improve the aim point of the weapon. Such terminal phase systems typically include a seeker or imager system. These provide additional data for use with target recognition or scene-matching algorithms. The UK Brimstone (Ref 15) and the US Longbow Hellfire (Ref 17) anti-armour weapons use millimetre-wave radar seekers and target recognition algorithms to search the ground for signatures corresponding to a specific target set. Since such seeker/imager systems are weapon mounted, they are likely to be relatively small and preferably low cost. A large, high resolution imaging system would be expensive to install and is likely to compromise the size of other weapon systems (e.g. the warhead and/or the propulsion unit). Consequently, the seekers and imagers fitted to autonomous weapons tend to have limited resolution and restricted search areas. It is therefore imperative that the initial estimate of target location is accurate enough for the target to fall within the search area of the weapon seeker. For systems without such terminal phase corrections, the accuracy of the initial estimate of target location is even more important because even small errors cannot be corrected at a later stage.

Mobile or relocatable targets present a very challenging problem because their estimated position will generally be determined using information (position and velocity) obtained before weapon launch. This is particularly important where the target information is supplied by a third party and is not corroborated by a sensor on-board the attack aircraft. Time delays in passing the information from the third party to the attack aircraft, and the associated delays in verification (Command, Control, Communication and Intelligence - C^3I - delays) all add to the uncertainty in target position, and therefore limit the effective stand-off range of the weapon system, as shown schematically in figure 3. As the stand-off range and the time of flight of autonomous weapons are increased, the ability of mobile targets to manoeuvre, between fixing the target position and the weapon arriving at that position, will be a major factor in determining the performance of autonomous weapons. Some weapons may have datalinks, which allow target information to be updated mid-flight or 'man-in-the-loop' control of the terminal phase, but this adds to the requirement for an extensive communications and support infrastructure, which may reduce the flexibility of the weapon system. Without this ability to update target position mid-flight, the effective stand-off range of any autonomous anti-armour weapon will be limited by C^3I time delays, the weapon time of flight and the ability of the targeting system to predict the movement of the target.

For example, a Main Battle Tank (MBT) moving at an average 30 km/h across country will travel approximately 500 metres in one minute. With no estimate of its speed or its direction of travel, a subsonic missile (fired at a range of around 15 km and travelling at an average 200 m/s) would be required to search an area approximately 1200 metres across to allow for the error in the estimated target position. Where an estimate of the target velocity is available, the natural variations in speed across country are likely to be at least 10% of the average speed, even without any additional manoeuvres by the MBT. This reduces the area to be searched, but a 60 metre error (assumed Gaussian) in target position would still require a search area approximately 200 metres across to be 90% confident of including the target in the seeker field of view. This problem is accentuated if there are significant delays between the target position being fixed and the information being passed to the attack aircraft. Doubling the delay between the target position being fixed and the weapon arriving at the estimated location will double the dimensions of the search area. One possible way of reducing this error is to increase the speed of flight of the missile; doubling the speed of the weapon reduces the required search area by a factor of four. However, this also reduces the time available for the search to be conducted. This puts additional demands on the seeker/imager control and detection systems and increases the computational load proportionately.

Figure 4 shows the probability for a target to be within the seeker search area for a missile with search width of 200m for a range of time delays and assuming a target speed error of 3 km/hr. There is a significant drop in the probability of the target being in the search area for time delays of more than a minute or so. If one were to include a figure for the performance of the seeker system and the associated target detection algorithms into account, it is possible to obtain an estimate for the performance of an autonomous weapon system. However, even with an ideal seeker system, the performance will always be limited by the ability to estimate the current position and motion of a target, and to predict its position when the weapon arrives at the target.

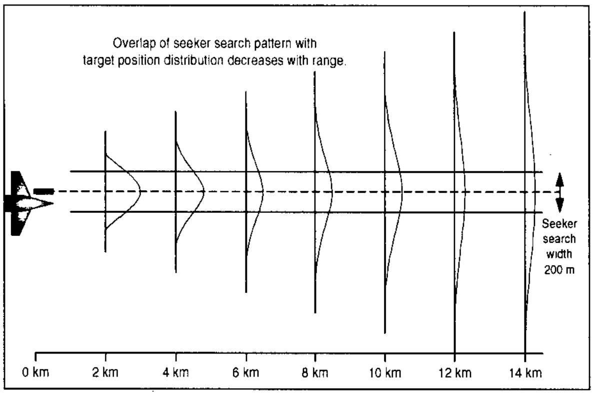

Figure 3: Schematic diagram showing targeting errors as a function of stand-off range

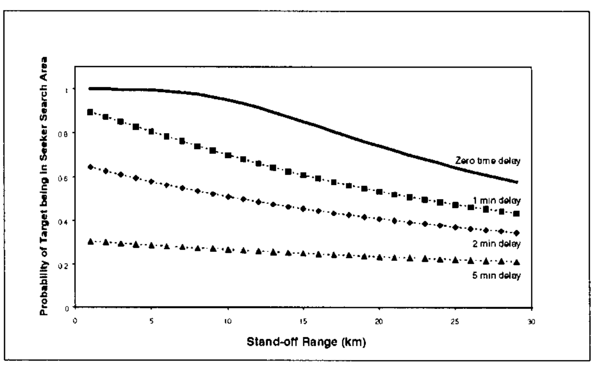

Figure 4: Probability of a target being within the seeker search area vs. stand-off range for different C^3I/datalink time delays (seeker search width 200m, target velocity error 3 km/h)

This example has shown how critical is the availability of up-to-date, highly accurate target data to the attacking aircraft. At the present time the method of supply of this information is as it has been for some decades - by radio. This is open to error at all stages - transmission, receipt, transcription, and finally, entry by the aircrew into the aircraft nav-attack system. The process is also undesirably time consuming. An evolutionary method of partial amelioration of this process is to send the targeting information digitally to the attacking aircraft, so that it is available quickly, directly and in the format required by the weapon aiming avionics.

12 UTILITY OF DIGITAL DATA INTO THE COCKPIT

The application of air power in current and future military engagements is taking on a far greater requirement for rapid response to on-call tasking. Previously, in the so-called 'Cold War' scenarios, much of the application of air power would be against large, fixed sites using pre-planned options for attack. Alternatively the attack of armour would involve Close Air Support aircraft being directed at relatively large numbers of targets occupying known terrain. The end of the Cold War has changed much of this with the accent now turning to Operations Other Than War (OOTW) or Peace-Support Operations (PSO). Here the requirement for precise targeting against mobile, unitary targets has grown significantly with a concurrent emphasis on the constraints on weapon delivery through Rules of Engagement.

Two factors may be identified in the application of air power in typical OOTW situations; firstly the requirement to bring fire rapidly to bear on a target that unscreens at very short notice and secondly the requirement to strike a target with great precision given ROE constraints where the risk of collateral damage is unacceptable. The key to the solution of both tasks is the ability to provide timely information to the cockpit of an aircraft that allows the pilot to deliver ordnance at short notice but still with great precision. The requirement for aircraft survivability is a further constraint on the time available in the target area for acquiring and engaging the target.

The speed with which an aircraft can respond to a call for fire-support is a function of a number of factors. The assets available are the major element; does the situation warrant having suitably-armed aircraft on near constant patrol able to respond to any engagement required in the area of responsibility? If ROE preclude patrols by aircraft carrying anything other than self-defence weapons then the timeline in preparing and launching offensively-armed aircraft will be a major factor. It must also be assumed that the relevant surveillance platforms are already airborne and on station such that the unmasking of a potential target (isolated tank emerging from hide, for example) will be detected in reasonable time.

Given that round-the-clock surveillance capable of that level of detection is not a reality, and that the availability of armed aircraft may be, at best, from ground readiness, the time available to prosecute a response is very short. Time for pre-planning may not be available, so that the first the pilot learns of the nature of the target and task is after becoming airborne and having been vectored towards the target area. The problem now is in providing the pilot with the required information, during a possibly short transit time, to carry out a successful first-pass attack within the constraints of the ROE in use.

The task of Close Air Support has been carried out by having an observer (a Forward Air Controller [FAC]) on the ground passing information on the target to the pilot over a voice radio. There are a number of problems and limitations with this, primarily that of establishing and maintaining communications. Obscuration of line-of-sight for an aircraft manoeuvring at low-level often leads to temporary losses of communication with the FAC. The perspective of the target from the ground is very different from the air and extensive training is required to enable the FAC to interpret the scene and then describe the attack run to the pilot in terms of what the pilot will see.

The tasking message sent to the pilot will include a number of elements which have to be manually written

down by the pilot. This is generally referred to as the '9-Line Brief' and has the following format:

Line	Example
CALLSIGN	STRIKER 1/2
TARGET	BRIDGE
DMPI	CENTRE SPAN
TARGET POSITION	N 52D45.00 004D55.00 W
TARGET ELEVATION	00566 FT
BEST ATTACK HEADING	255
IP POSITION	WP 455
LASER CODE	1334
NOTES	FRIENDLY FORCES 3 KM SOUTH. EGRESS HDG 355

The DMPI is 'Desired Mean Point of Impact' and is the part of the overall target the weapons are required to impact. The laser code is used by laser guided weapons to identify the correct laser 'spot' when several designations are occurring simultaneously.

The pilot then locates the target area on the map and tries to tie that in with verbal instruction from the ground whilst still flying the aircraft in probably hostile airspace. The ability to automate the entire task would be highly desirable. It is with the advent of high capacity digital data transmission that this is now possible.

The recent, rapid development in Information Technology has led to the development of small, lightweight laptop computers with software designed to process and manipulate digital imagery. Modem cards enable digital data to be transmitted over telephone networks or across radio bands. By linking a number of Commercial, Off-The-Shelf (COTS) equipments it is now possible to transmit to an aircraft a complete tasking message for display to the pilot. By careful design of the man-machine-interface the weapon aiming task may be made an entirely 'heads-out' procedure, thus obviating the need either to look into the cockpit or, indeed, write anything down.

A typical scenario would be as follows:

A UN patrol on peace-keeping duties suddenly comes under rocket and small-arms fire from local militia who have taken over a deserted house about a kilometre away. The patrol are pinned down and call for air support. In-use ROE permit the attack of the building but positive, visual, identification of the building must be made prior to releasing weapons. An aircraft at 5 minutes readiness, and armed with 2 Paveway II laser-guided bombs (LGBs), is scrambled for the task. At this stage the pilot knows nothing of the specifics of the task other than the approximate area to which he is to fly. Take-off and initial routeing is all performed using standard operating procedures.

After checking in with AWACS via secure radio the pilot is given a brief, verbal description of the task and a tactical frequency for the mission. Ten minutes outbound from the target area the aircraft is cleared to tactical frequency. The pilot transmits callsign, weapon load, ETA and time-on-station to the patrol via digital data-link transmission lasting less than 50 milliseconds. The patrol receive the 'handshake' where the patrol leader has already pre-prepared a tasking message on a ruggedized laptop connected via modem to the patrol UHF radio. The laptop also has a feed from a GPS receiver continually fixing the patrol's position to less than 10 metres. The patrol leader uses a digital camera with telephoto lens to capture an image of the building; the image is down loaded to the laptop along with the exact position of the building taken by a co-boresighted laser range-finder. The entire message 'package' is then transmitted to the aircraft over the digital data-link. On receipt in the aircraft the message is de-modulated and transferred by 1553 databus to the aircraft weapon aiming computer.

The pilot sees an aiming cue in the HMD indicating where to look to see the target. Simultaneously the laser designation pod slews to the target position providing a thermal image of the building and its surrounds. The image of the target area, taken by the patrol, appears on a second head-down display showing the exact building and warning the pilot of a similar structure 150 metres away not to be hit. Cross referencing the designator image with the target photo the pilot confirms the exact aiming point, locks the laser tracker and releases the weapon. The building is hit by a single LGB a few seconds later and all enemy fire ceases. As the aircraft egresses the area the patrol takes a number of further images of the targeted building and data-links these through the AWACS for onward transmission to the command HQ for post-strike analysis.

13 AUTOMATIC TARGET RECOGNITION

The workload of the pilot in the above example is eased by the use of timely digital targeting data. It may be further eased by the use of automatic target recognition algorithms. These make use of advanced aircraft computing power and the evolution of highly inertially stable, narrow field-of-view imaging sensors. Currently at Generation 3, research is taking place into 4th generation sensors which will enable target recognition at several kilometres. Since the aircraft's TRN/GPS/INS will give ownship position to a few metres, the imaging sensor may be pointed with high accuracy at the (approximate) target location some kilometres distant, and then automatically steered around that position to enable target acquisition. In the earlier MBT example, target information would typically be totally, or at least enhanced with, digitally-received up-to-date data. In the case of an attack against a fixed target, the target details and the geography and the features around the target may be foreknown through a variety of sources, for example, FAC, map, satellite imagery, reconnaissance photographs, stand-off radar etc. The real-time aircraft perspective imagery may then be matched real-time with the foreknown target data in order to give high confidence in the position of the target (for example, in relation to immediately local features), the type of target (for example, a SCUD launcher), or the precise part of the target (for example, a room in a building). The

pilot's task is then fully automated up to that of final consent, if the ROE require. Furthermore, to the extent that pilot input may be required during the target search phase, the input may be made by direct voice input, thus leaving the hands totally free on the throttle and the stick. Thus only the final commit to weapon release will be performed manually.

In addition to being of high utility during the attack phase, the ability to point an imaging sensor, with high confidence, at a known location is of great benefit for two other purposes. The first is that of aerial reconnaissance, either planned, by a reconnaissance aircraft, or seen on a 'target of opportunity' basis by an aircraft executing some other mission. Such capability should not be underestimated: this aspect of war has changed little since the end of WWI when the offensives by which the allies drove the Turks from Palestine and Syria in 1917 and 1918 were planned and executed in the light of expert scrutiny of air photographs of the Turkish lines (Ref 18). The second purpose, partly a subset of the first, is that of bomb damage assessment. In this case the attacking, or designating (spiking), aircraft itself records the effect of the attack in order to determine the need for further action.

14 CONCLUSION

Ground attack from heavier-than-air craft, and ground counter-attack, began in 1914. Since then the speed of ground attack aircraft has increased by a factor of 5-10, and the weapon load by a factor of approximately 500. Early, crude aircraft weapons have been replaced, by laser-designated weapons and, most recently, by autonomous tactical weapons with a stand-off capability of some kilometres.

Rules of Engagement, particularly in operations other than war, require positive target identification and accurate targeting in order to minimise collateral damage. Automatic target search and acquisition by on-board aircraft sensors is of high value to facilitate rapid compliance with the Rules of Engagement. Targeting, or aiming, through the HUD, although highly accurate for ballistic weapons, is less viable at high stand-off ranges and not possible at all when using the full off-boresight capability of modern weapons. In the latter case the HMS and HMD are of proven high utility for line-of-sight stand-off weapons.

Ground defences, even those of a portable nature, may be sophisticated and potent. If the attacking aircraft can 'see' (be line of sight to) the ground target, then the aircraft may be seen by the target's defences - in fact the aircraft is probably more easily visible against its uncluttered background than is the target against its ground backdrop. Defended mobile armour is particularly difficult to target, or designate for attack, by an autonomous weapon since it can move outside of the weapon's search pattern within the weapon's time of flight.

Up-to-date targeting data, transmitted by a third party digitally to the cockpit of the attacking aircraft is of extremely high utility in enabling target acquisition and designation at a safe stand-off range. Rapid assimilation of this information by the pilot, and automatic use by an integrated weapon aiming avionic suite, will ensure minimal time spent within the engagement zone of air defences. Automatic incorporation and consolidation of target data from a variety of third party sources will further minimise the time taken for target acquisition, recognition and designation, and subsequent weapon release. Air defences and stand-off ranges will improve incrementally, more or less in unison, and the use of third party targeting via digitally-transmitted data is perceived as a growing requirement.

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REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's References	3. Further Reference	4. Security Classification of Document
	RTO-MP-16 AC/323(SCI)TP/8	ISBN 92-837-0007-4	UNCLASSIFIED/ UNLIMITED

5. Originator Research and Technology Organization
North Atlantic Treaty Organization
BP 25, 7 rue Ancelle, F-92201 Neuilly-sur-Seine Cedex, France

6. Title
Aircraft Weapon System Compatibility and Integration

7. Presented at/sponsored by
the Systems Concepts and Integration Panel (SCI) Symposium held in Chester, United Kingdom, 28-30 September 1998.

8. Author(s)/Editor(s)	9. Date
Multiple	April 1999

10. Author's/Editor's Address	11. Pages
Multiple	256

12. Distribution Statement There are no restrictions on the distribution of this document. Information about the availability of this and other RTO unclassified publications is given on the back cover.

13. Keywords/Descriptors

Weapon systems
Military aircraft
Integrated systems
Compatibility
Flight tests
Computational fluid dynamics
Wind tunnel tests
External stores
Trajectories
Mathematical models
Computerized simulation
Separation
Structural analysis
Aerodynamics
Aerodynamic loads

14. Abstract

Economic constraints dictate that the lives of existing aircraft must be stretched, making the incorporation of new weapons and weapon systems into existing airframes necessary. These same constraints dictate that the corollary is also true, i.e. that new aircraft must cope with existing weapons as well as their new systems. Along these lines, the goal of this symposium was to critically review the overall state-of-the-art in aircraft weapon system compatibility and integration for the benefit of researchers, RDT&E managers, engineers, and operational staff employed by both contractor and supplier organisations within NATO. Illuminating possible paths for future development and providing beneficial ideas and experience was achieved as part of the overall objective of the symposium. Also, the symposium explored both fixed and rotary wing applications as they related to the above mentioned session areas. Overall, the attendees were quite pleased with the presentations along with a very informative roundtable discussion.

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publié par le National Technical Information Service
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(accessible également en mode interactif dans la base de données bibliographiques en ligne du NTIS, et sur CD-ROM)

Imprimé par le Groupe Communication Canada Inc.
(membre de la Corporation St-Joseph)
45, boul. Sacré-Cœur, Hull (Québec), Canada K1A 0S7

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Printed by Canada Communication Group Inc.
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ISBN 92-837-0007-4